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COMMUNICATION AND TRACKING COVERAGE

FOR THE REENTRY PHASE OF

APOLLO LUNAR MISSIONS

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Section 1

INTRODUCTION

PURPOSE AND CONTENT OF REPORT

This report is concerned with communication and tracking coverage objectives during the reentry and late portions of the trans-Earth trajectory (henceforth called "pre-reentry") phases of Apollo lunar landing missions. Specifically, the purposes of this report are:

1. To provide a technical basis for evaluating and comparing the potential utility of various land locations and of various numbers and locations of ships as communication and tracking stations during the reentry and pre-reentry phases
2. To provide a similar technical basis for evaluating and comparing several Earth landing sites for the Apollo Command Module on the basis of communication and tracking coverage.
3. To indicate in general terms the instrumentation requirements for stations intended to provide communication and tracking coverage during the reentry and pre-reentry phases.

The results of this study should be accepted in the light of certain objectives and assumptions that form the basis for the analysis. In order to set a background for understanding the summary and conclusions in Section 2, therefore, statements of the objectives for communication and tracking coverage adopted in this study, as well as the basic assumptions used in the analysis, are included as part of this introductory section.

Comprehensive sets of trajectories and their associated ground tracks have been generated for each of eight landing sites studied. These trajectories cover fairly uniformly the range of geometrical relationships allowed by the assumptions listed in the section entitled, Basis Assumptions Used In Coverage Analysis. Thus, meaningful comparisons may be made among the landing sites with regard to mission flexibility and coverage capabilities.

Sections 3 and 4 discuss objectives, ground tracks, station coverage capabilities, and instrumentation requirements during the pre-reentry and reentry phases, respectively. The mechanics of generating the trajectories and ground tracks used in the station coverage analyses are discussed in Appendices A and B. Appendix C is a listing of certain abbreviations and other terminology used frequently in the report; it is suggested that the reader refer to this appendix before proceeding further.

OBJECTIVES FOR COMMUNICATION AND TRACKING COVERAGE

The basic objectives of communication and tracking (C&T) stations during the mission phases of interest in this report are considered to be the following:

During Pre-reentry

1. To provide a period of tracking and communication with the spacecraft during and after the last mid-course correction but before the separation of the Command and Service Modules. Current estimates of the time when the last mid-course correction will occur range from one to three hours before reentry.

2. To provide a period of tracking and communication with the Command Module during and after the jettisoning of the Service Module but before reentry. Current estimates of the time when jettisoning will occur range from 10 to 30 minutes before reentry. This report is not concerned with tracking of the Service Module after jettisoning.

The combination of objectives 1 and 2 is aimed at obtaining an accurate prediction of the trajectory in the vicinity of the reentry point, assessing the condition of the spacecraft and occupants during and following the events noted, and providing ground-derived data that may be useful in guiding the Command Module during reentry.

During Reentry

1. To collect sufficient information about the trajectory of the Command Module to make an estimate of the landing point which will permit expeditious recovery

2. To provide communications with the Command Module

The degree to which these reentry objectives are met, as well as those applying to the pre-reentry interval, ultimately involves a balance with limitations imposed by natural phenomena and economics.

BASIC ASSUMPTIONS USED IN COVERAGE ANALYSIS

There are a number of assumptions, beyond those implied by the above statements of objectives, which significantly affect the results of the coverage analysis in this report. The assumptions which are of particular importance to a proper interpretation of the Summary and Conclusions in Section 2 are the following:

1. The lunar landing missions considered are those for which the trans-Earth trajectory and the time of reentry are within limits as defined below, and are predictable at the time of leaving the Moon. It is assumed that time of departure from the Moon can vary by as much as three days. It is further assumed that mid-course corrections will adjust for any inaccuracies in injection so that the predicted conditions at the reentry point will be obtained.

2. Pre-entry and reentry coverage considerations initially should not be allowed to place restrictions on the time when an Apollo mission can be conducted. If the number, locations, or instrumentation of stations required to meet the previously stated objectives turns out to be economically or technically unreasonable, trade-offs between objectives and mission flexibility should be considered.

3. Trans-Earth trajectory inclination angles relative to the Earth's equator will be restricted to a maximum of 40 degrees; this is to assure landing in a temperate climate. Ultimately, restrictions on fuel budgets, coupled with restrictions on lunar parking orbit configurations, may limit the allowable inclination angles.

4. The minimum flight time from trans-Earth injection at the Moon until reentry at an altitude of 400,000-feet is considered to be 60 hours, and the maximum time is considered to be 110 hours. The minimum is set by fuel-budget restrictions and is currently in an undetermined state; however, indications are that it is likely to increase as Apollo mission plans materialize. The general effect of a longer return time would be to ease the reentry coverage problem. The ability to vary flight time by at least 24 hours insured that a specific landing site (on a rotating Earth) will be in its proper spatial orientation at the time of landing.

5. The range from the reentry point to touchdown may vary from approximately 1200 to 5000 nautical miles. The shorter range is set by g-limits on the spacecraft; the longer range by guidance system accuracy considerations.

6. Reentry flight profiles, following an initial descent to an altitude near 200,000 feet, will follow a ballistic lob trajectory, a constant-altitude trajectory for a large portion of the reentry path length, or a short-range emergency trajectory.
7. All coverage for tracking purposes is based on a visibility, or masking, limit of 5 degrees above the horizon at the tracking station.

Section 2

SUMMARY AND CONCLUSIONS

The capabilities of various land and ship stations to both track the Apollo spacecraft and communicate with it during the latter part of the trans-Earth trajectory have been examined. As a starting point for the study, it was necessary to calculate trajectories and related ground tracks terminating at selected landing sites. Sets of ground tracks were generated for the following typical landing points:

1. Southwestern U.S., near San Antonio (29.5°N, 99°W)
2. Woomera, Australia (29.5°S, 135°E)
3. Pacific Ocean, near Hawaii (20°N, 150°W)
4. Pacific Ocean, near Samoa (10°S, 170°W)
5. Pacific Ocean (10°N, 130°W)
6. Pacific Ocean (10°S, 130°W)
7. Pacific Ocean, on the Equator, near Panama (0°, 85°W)
8. Atlantic Ocean, near Antigua (17°N, 60°W)

The first four sites in this list have been mentioned (Ref. 4) as possible candidates for Apollo Landings, the first two as a paired set of land sites to accommodate landings throughout a month, and the next two as a paired set for water landings. (Although the specific coordinates cited may not agree precisely with those mentioned elsewhere, they are typical.) The two Pacific Ocean sites at 130°W longitude were chosen in this study to show the possibilities of coverage by ships for a pair of sites symmetrically spaced from the equator but not in an area where ship movement would be restricted by land masses. The equatorial site was chosen with a similar objective of showing the possibilities of ship coverage for a single site which might accommodate landings on any day of a month, weather permitting. Finally, the site near Antigua was chosen to illustrate the coverage that would be possible using existing land stations in the U.S. and along the Atlantic Missile Range.

Ground tracks corresponding to reentry trajectories terminating at each of the landing sites listed above are illustrated in Section 4. From the viewpoint of achieving the greatest flexibility in accommodating landings, including total days of a month and widest spread of inclination angles on most days, a site on the equator is the best single choice. Sites at latitudes progressively farther from the equator tend to eliminate landings on days near one or the other lunstice of the Moon's orbit. However, the spread of trajectory inclination angles available on some days is increased, the increases occurring during the southern-lunstice (SL) half of the lunar month for northern latitude landing sites, and during the northern-lunstice (NL) half of the month for southern latitude sites. This suggests that even wider mission flexibility may be provided by a suitably-chosen pair of landing sites, one north and the other south of the equator, than would be provided by one site on the equator.

There are some penalties involved in making such a choice. One penalty is the elimination of trajectory inclinations smaller than the latitudes of the sites. Another penalty may be the necessity for two groups of reentry tracking and recovery forces; this depends on how far apart the chosen sites are, particularly in longitude.

The results of the pre-reentry and reentry coverage analyses will be summarized separately in the following paragraphs. The stations assumed in the analyses include, in addition to ships in various ocean areas, the following land stations:

Near-Earth or Extended-Range Stations	Deep-Space Stations
Cape Kennedy	Goldstone
Bermuda	Madrid
Grand Bahama	Canberra
Grand Turk	Johannesburg
Antigua	
Ascension	
Carnarvon	
Guam	
Hawaii	
Pt. Arguello, Calif.	
Corpus Christi, Texas	

All stations in the above list either exist now or have been suggested at one time or another as parts of the Manned Space Flight Network (MSFN), the Atlantic Missile Range (AMR), or the Deep-Space Instrumentation Facility (DSIF). While Johannesburg, a DSIF station, is intended primarily to serve unmanned deep-space missions, it was included in this study because of its particular suitability for filling a gap between the coverage limits of Madrid and Canberra for certain pre-reentry trajectories.

PRE-REENTRY COVERAGE

Summary

Communication and tracking coverage of pre-reentry trajectories is analyzed in Section 3. Table 2-1 summarizes the coverage that can be provided by the land stations for six of the eight landing sites assumed above. Pre-reentry coverage data for the pair of sites at ±10° latitude, 130°W longitude, were also analyzed but were not tabulated for this presentation because their general characteristics are similar to those for the Samoa and Hawaii sites.

Table 2-1 shows the average time before reentry that continuous visibility is lost for trajectories terminating at a given site, as well as the earliest loss of continuous visibility among all the trajectories considered. The top half of the table summarizes the coverage provided by the combination of the three deep-space sites at Goldstone, Madrid, and Canberra. The bottom half of the table shows how the coverage is extended by also considering the coverage offered by the shorter-range stations. For some trajectories, there are one or more gaps in the pre-reentry coverage between the time of visibility loss by deep-space stations to the final loss of visibility. The average of the total out-of-contact time is indicated in the third line in each half of the table, including the gaps prior to final loss of contact by any station and the time between final loss of contact and the reentry point. A detailed tabulation of final loss of visibility and total out-of-contact times for each trajectory is given in section 3.

One of the objectives for pre-reentry coverage mentioned in Section 1 is to track and communicate with the spacecraft during and after the last mid-course correction, and before the Command Module-Service Module (CM-SM) separation. Deep-space stations at Goldstone, Madrid, and Canberra can provide at least 13 minutes of such coverage for all trajectories to all landing sites except Hawaii and Samoa, based on the last mid-course correction occurring as late as one hour before reentry and the CM-SM separation occurring as early as 30 minutes before reentry. Coverage by these deep-space stations cannot be guaranteed for about 48% of the trajectories to the site near Hawaii and for about 20% of the trajectories to the site near Samoa if the last mid-course correction can occur at any time between one and three hours before reentry. However, at least 16 minutes of coverage can be provided for all trajectories to Hawaii and Samoa, and at least 30 minutes to all other sites if the following holds true:

Table 2-1

SUMMARY OF PRE-REENTRY COVERAGE PROVIDED BY LAND STATIONS

	Landing Site at:					
	San Antonio	Woomera	Hawaii	Samoa	Antigua	Panama
Coverage Provided by Goldstone, Madrid, and Canberra						
Average time before reentry for loss of continuous coverage (minutes)	9.3	14	76	50	13	18
Earliest loss of continuous visibility, minutes before reentry	15	22	231*	211*†	29	47
Average of total out-of-contact time (minutes)	9.3	14	67	40	11	16
Combined Coverage Provided by Deep-Space and Near-Earth Stations						
Average time before reentry for loss of continuous coverage (minutes)	6.6	14	4.4	15	8.7	5.5
Earliest loss of continuous visibility, minutes before reentry	14	22	20	43	21	13
Average of total out-of-contact time (minutes)	6.6	13	4.4	11	8.6	5.3

*The earliest loss of visibility can be reduced to 63 minutes for Hawaii landings and to 45 minutes for Samoa landings if Johannesburg is added to the list of deep-space stations.

†There are short gaps in deep-space coverage earlier than 211 minutes for the Samoa site for a few trajectories. However, none is longer than about 3 minutes; hence they are ignored here.

1. Stations at Carnarvon and Guam have the ranges indicated later in Table 2-3.

2. The deep-space station at Johannesburg is made available.

3. A ship having about 32,000-mile range capability is made available in the western area of the Indian Ocean.

The ability to achieve the objective of tracking and communicating with the CM during and after jettisoning of the SM is indicated in Table 2-2. This table gives the percentage of tracks for which this objective can be met, assuming the use of both deep-space and shorter-range stations of the MSFN, and assuming at least five minutes of coverage is desirable after the SM separation and before reentry.

Table 2-2

PERCENTAGE OF TRAJECTORIES HAVING AT LEAST FIVE MINUTES OF COVERAGE AFTER SM SEPARATION

	Time Between SM Separation and Reentry		
Landing Site	30 Min.	20 Min.	10 Min.
San Antonio	100	100	24
Woomera	100	58	0
Hawaii	100*	98*	74*
Samoa	98*	66*	66*
Antigua	100	84	30
Panama	100	100	53

*Considered as paired sites, with landings at Hawaii from SL through the Node days, and at Samoa for the balance of the month, the percentages of all trajectories covered are 100% for separation at 30 minutes, 97% at 20 minutes, 80% at 10 minutes.

The coverages indicated by Tables 2-1 and 2-2 are based entirely on 5°-above-the horizon visibility limits, without consideration of range requirements for specific stations. Insofar as deep-space stations are concerned, range capability presents no problem. The range requirements for the non-deep-space stations are as indicated in Table 2-3. The maximum range for any station is about 32,000 nautical miles, which is required at Carnarvon to cover certain trajectories terminating at Hawaii. This range requirement could be reduced to about 4000 miles (and the range requirement for Samoa landings to about 7000 miles) if the deep-space station at Johannesburg were made available. The Carnarvon range could also be reduced if a ship with about 32,000-mile range capability were made available in the Indian Ocean.

The range requirement for ground stations after the jettisoning of the SM is of special interest because of the loss of the directional antenna which is to be mounted on the SM. The longest range from a ground station at which the jettisoning can occur is 6700 miles, if this event occurs 30 minutes before reentry and if the spacecraft then is at the limit of visibility for a 5° station masking angle. Ranges at or very near the maximum of 6700 miles are required at Carnarvon for landings at Hawaii and Samoa, and at Guam for landings at Samoa and the equatorial site near Panama. For all other combinations of landing sites and C & T stations, the maximum ranges as indicated in Table 2-3 occur after the CM-SM separation, if this event occurs as early as 30 minutes before reentry.

Table 2-3

SUMMARY OF RANGE REQUIREMENTS FOR NON-DEEP-SPACE STATIONS PRIOR TO REENTRY

	Slant Range (nm) Required for Landing at:					
C&T Station	San Antonio	Woomera	Hawaii	Samoa	Antigua	Panama
Carnarvon	2,400	1,100	32,100*	26,700*	-----	-----
Guam	3,000	-----	4,600	8,700	-----	7,800
Hawaii	3,700	-----	---	---	5,300	2,200
Ascension	---	2,200	---	---	---	---
Pt. Arguello	---	---	---	---	3,300	1,200
Corpus Christi	---	---	---	---	2,200	---

*Carnarvon's range can be reduced to 4,000 nm for Hawaii landings and 7,000 nm for Samoa landings if the Johannesburg deep-space station can be used, or if a ship having about 32,000-mile capability is available in the Indian Ocean.

Pre-reentry coverage by land stations for Woomera landings can be supplemented significantly by a ship located in the northern area of the Indian Ocean. Except for this landing site, however, ships appear to offer no great advantage in providing pre-reentry coverage over that which can be provided by land stations with the range capabilities indicated in Table 2-3.

PRE-REENTRY COVERAGE

Conclusions

With regard to tracking and communication coverage of the pre-reentry trajectories, the following conclusions are drawn:

1. Extended-range stations at Carnarvon (32,000 nm capability) and Guam (8700 nm capability) would add significantly to the coverage capabilities of deep-space stations for landings near Hawaii and Samoa. These stations could also contribute substantially to the coverage for landings at the ±10° latitude pair of sites and the equatorial site considered in this report. Hawaii, Ascension, Pt. Arguello, and Corpus Christi can contribute limited pre-reentry coverage for some landing sites.

2. If a deep-space station in the vicinity of Johannesburg were used, or if a ship having about 32,000-mile range capability were available in the western area of the Indian Ocean, the range requirement at Carnarvon could be reduced to about 7000 miles.

3. Deep space stations supplemented by other appropriate stations, including extended range stations at Carnarvon and Guam, can provide adequate tracking and communication periods between the last mid-course correction and the CM-SM separation. At least 15-30 minutes can be provided for each landing site considered.

4. The objective of providing five minutes of coverage after the CM-SM separation can be achieved for all landing sites considered if the separation occurs at least 30 minutes before reentry. If the separation takes place less than 30 minutes prior to reentry, the 5-minute objective cannot always be achieved, as shown in Table 2-2.

REENTRY COVERAGE

Summary

One of the immediate conclusions reached from a study of the reentry ground tracks in Section 4 is that continuous communication and tracking coverage of all possible trajectories from the reentry point to the landing point is impractical, due to the large areas of the Earth spanned by these trajectories and the low spacecraft altitude in this interval. Thus, it becomes necessary to decide where the coverage of a reentry trajectory is apt to be most critical.

The solution discussed under OBJECTIVES FOR REENTRY COVERAGE is aimed at providing a period of tracking beginning approximately when the spacecraft reaches the minimum altitude (called "trough" in this report) in its initial descent into the atmosphere. This tracking is intended to determine whether a nominal or emergency mode trajectory is being flown, and to estimate the landing point. If the emergency mode is adopted, the station will be in a position to track the spacecraft through a substantial part of its remaining flight. Depending on the severity of reentry plasma effects, the station may also be able to communicate with the spacecraft at some time while it is within the station's visibility limits.

For most of the reentry tracks presented in Section 4, the desired location of a tracking station to cover an interval starting immediately after the initial reentry descent occurs in an ocean area. Thus, if coverage is to be provided without seriously restricting mission flexibility, it could be provided by appropriately instrumented ships.

COVERAGE BY SHIPS, in Section 4, discusses the extent of coverage possible for landings at the five Pacific Ocean sites chosen for analysis, using one to three ships suitably deployed over the area spanned by the reentry trajectories to those landing sites.

The analysis is in two parts. In the first part, ship coverage is studied under an assumption that landings will occur only on a specified nominal day. In the second part, landings are assumed also possible one day earlier and one day later than a nominal day.

It is found that one ship alone can provide the desired coverage after the initial reentry descent for all possible trajectory inclinations on some days. Further, it can provide coverage of a large majority of the possible trajectory inclinations on the remaining days of the month.

A second ship can substantially complete the coverage of the available spread of trajectories on most days. The additional coverage made possible by a third ship ranges from a fraction of a degree to about 4 degrees of trajectory inclination on some days. This third ship can also track some of the same trajectory inclinations covered by either the first or second ship; these trajectories have two possible reentry points within the reentry range limits of 1200 to 5000 miles. The only significant difference between the cases of the two reentry points, other than the length of their associated reentry trajectories, is a time difference of as much as three hours in the time of departure from the Moon and/or in the trans-Earth flight time. This magnitude of time variation seems well within tolerable limits for a nominal Apollo mission.

The analysis indicates that the same ships that can provide reentry coverage for a site near Samoa can also provide the coverage for a site near Hawaii under the following condition: The transition from landings at one site to landings at the other is made at a time when the spacecraft's departure from the Moon occurs between the days NL ± 6 and the Node. However, an appreciable percentage of the reentry points for trajectories terminating at Samoa on days near the northern lunstice fall over Australia and New Guinea. Other means of coverage would have to be provided in this area for landings at Samoa, or else mission flexibility would be hampered.

In like manner, the same ships that can provide coverage for one of the sites at ± 10° latitude, 130° W longitude can also provide coverage for the other, provided again that landings are shifted from one site to the other at a time near the Node of the Moon's orbit. These sites were chosen for analysis deliberately to assure unrestricted ship movement, since there are only small islands in the reentry ground track complex.

In the case of Southwestern U.S. and Australia used as a paired set of landing sites, the same reentry ships could not cover both areas unless there is an interval of weeks between the times when either one or the other site would be used for a landing. However, if one or more ships are provided in the Indian Ocean to serve earlier phases of an Apollo mission, as discussed in Reference 5, they can be redeployed in time to serve the reentry phase as well for a landing at Woomera.

In Section 4, under C & T INSTRUMENTATION REQUIREMENTS FOR SHIPS, some of the requirements for tracking communication and data processing facilities aboard reentry coverage ships are discussed in general terms. The discussion is colored by these technical and operational uncertainties:

1. The severity of the reentry plasma phenomenon to be expected during reentry
2. The extent of tracking and communication with the spacecraft that is needed during reentry
3. The ship-shore communication techniques that may be available

A brief assessment of the plasma attenuation problem indicates that VHF, S-band, and C-band frequencies are all likely to be blacked out during the major portion of some possible types of trajectories, while for other trajectories they may be useful for significant periods. On the basis that tracking is necessary at least during the period following the reentry trough, as assumed in the coverage analysis, and that voice, telemetry, and possibly up-data transmissions are desirable, certain instrumentation requirements for reentry coverage ships are specified. They include capabilities for both ionization sheath and beaoon tracking at C-band and a unified S-band tracking and communication system similar to that planned for certain Apollo land stations. VHF communications appear to offer little benefit during reentry and are not warranted on ships for reentry purposes alone.

Slant-range requirements for these tracking and communication facilities are indicated to be about 500 to 600 miles.

Shipboard data processing and ship-shore communication terminal facilities are left unspecified. These depend critically on the type of ship-shore communications that can be assumed available in the Apollo time frame. Communication satellites or airborne relay facilities are possibilities for more reliable, higher-capacity transmission channels than are now possible with the standard ship-shore radio facility today: HF radio. The point is stressed in C&T INSTRUMENTATION REQUIREMENTS FOR SHIPS that there is a question of trade-off between ship-shore communications and shipboard data processing facilities.

REENTRY COVERAGE

Conclusions

The reentry coverage studies reported here lead to an over-all conclusion that it is feasible to provide a reentry communication and tracking system of tractable size using ships as the primary C&T stations. Instrumentation and deployment of ships as outlined in Section 4, while not assuring a complete history of spacecraft position and condition during reentry, would go a long way toward removing the necessity for the IMCC to assume that the spacecraft had made a good trajectory and landing on the basis of a prediction made solely by pre-reentry tracking and communication information.

The specific conclusions regarding reentry coverage are these:

1. Continuous ground coverage from the reentry point to the landing point for all trajectories terminating at a given landing site is impractical.
2. A period of tracking starting no later than when the spacecraft reaches the trough of its initial reentry descent is necessary to determine the type of reentry trajectory being flown, and to estimate the landing point.
3. Ships offer a solution for providing the capabilities noted above. As many as three ships would be required to provide coverage for all possible reentry trajectories to a given site. However, two ships can probably provide enough coverage to avoid imposing serious limitations on mission flexibility.
4. One group of reentry ships deployed as described in Section 4 can serve two landing sites north and south of the equator, provided the sites are not too widely separated in longitude. Specifically, the sites near Hawaii and Samoa can be served by the same tracking ships, as could a pair of sites at ± 10° latitude, 130°W longitude.

5. The feasibility of beacon tracking and communication with the spacecraft during reentry is uncertain due to plasma effects, but the possibility for such tracking and communication is good for at least some types of trajectories. Reentry tracking ships should be equipped for both ionization sheath tracking and beacon tracking at C-band frequencies. Unified S-band beacon tracking and communication facilities should be provided for use when plasma effects permit. Ships should also have facilities to communicate with the IMCC. The extent of data-processing facilities required on the ships depends on the bandwidth and reliability of the ship-to-IMCC communication facilities provided.

Section 3

PRE-REENTRY COVERAGE

OBJECTIVES FOR PRE-REENTRY COVERAGE

For purposes of this report, the pre-reentry phase of an Apollo lunar landing mission has been defined as that portion of the trans-Earth trajectory extending from approximately 50,000 nm altitude to 400,000 feet altitude (the latter defined as the reentry point). This interval is expected to include two major events: the last mid-course correction, and the separation of the Command and Service Modules. The mid-course correction is expected to occur from one to three hours before reentry, and the CM-SM separation from 10 to 30 minutes before reentry.

Two principal communication and tracking objectives for the pre-reentry phase have been stated in the Introduction. The first objective is to provide a period of tracking and communication with the spacecraft during and after the last mid-course correction, but before the separation of the CM and SM. Tracking is needed following the mid-course correction to accurately predict the reentry point parameters. Communication is needed to assess the condition of the spacecraft and its occupants and to provide ground-generated information to assist in the reentry. Continuous coverage during the interval between the last mid-course maneuver and the CM-SM separation is not essential.

The second objective of the ground network during the pre-reentry phase is to track and communicate with the CM for an interval beginning before the start of the SM stage-off event and continuing on for about 5 minutes after the stage-off is completed. Coverage during this interval is desired to determine the extent to which the SM stage-off may have disturbed the CM trajectory, and to inform the CM of the resultant effect on predicted reentry conditions.

The coverage analysis in this section will indicate the possibilities of meeting the above objectives when landing sites and C&T stations are as listed in Section 2. Before coverage aspects are discussed, however, it is necessary to consider the trajectories and related ground tracks that apply.

PRE-REENTRY TRAJECTORIES AND GROUND TRACKS

The following paragraphs discuss in general terms the methods used in this study to generate pre-reentry altitude profiles and ground tracks. Examples of ground tracks terminating at various landing sites are included. More detailed explanation is given in Appendix A.

The accuracy required in calculating trajectories to be used in an analysis of ground coverage can be appreciably less than might be required for other purposes (for example, for analysis of spacecraft guidance problems). The approach taken, therefore, was to develop a relatively simple method of generating trajectories and related ground tracks. Appendix A discusses the simplifying assumptions used in the analysis.

Beyond the calculation of ground tracks, the methods described in Appendix A give the points of initial contact (CON) and loss of signal (LOS), or loss of visibility, for any assumed ground station and any specified antenna masking angle (5° has been used here). The entire procedure has been programmed for computer analysis, making it readily possible to assess the potential utility of stations other than those specifically assumed in this report, in terms of their coverage capabilities relative to any set of pre-reentry tracks.

Figure 3-1 shows a pre-reentry track computed for the following conditions:

1. Landing site at latitude 29.5° north, longitude 99° west (San Antonio, Texas)
2. Departure of the spacecraft from the Moon at Southern Lunstice (SL), the Moon's declination with respect to the Earth's equator being -28.5° at this time
3. Trajectory inclined 29.5° to the equator (this, in conjunction with the latitude of the landing site, resulting in a due-East approach heading at the landing site
4. Reentry flight path angle of -6.4°
5. Orbit eccentricity = 0.98.

Altitude and time ticks are shown at various points along the track. In addition, visibility limits are shown for a number of stations. This track, like all the pre-reentry tracks developed in this study, terminates at the reentry point. However, a reentry track as developed by the methods described in Appendix B for the same lunar-departure conditions has been added to illustrate the continuity of the two phases.

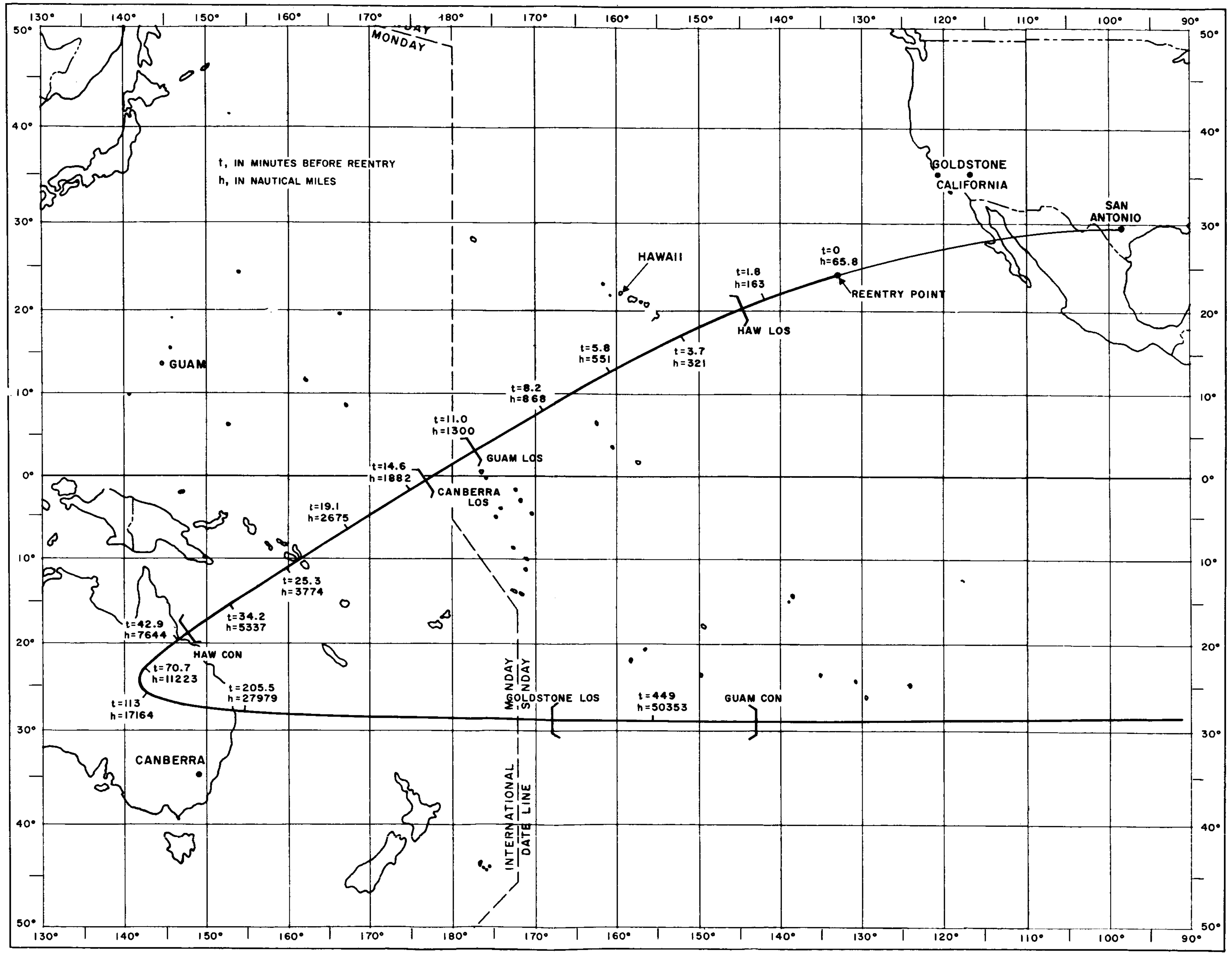

Figure 3-1. Example of Pre-Reentry and Reentry Track

An analysis of the sensitivity of pre-reentry ground tracks to changes in orbit eccentricity and reentry flight path angle is reported in Appendix A. Briefly, the results show that variations in these two parameters within limits considered appropriate for Apollo trajectories produce negligible effects from the viewpoint of pre-reentry coverage. Hence, all tracks used in the subsequent pre-reentry analysis were computed for nominal values of these parameters (0.98 for eccentricity, -6.4° for reentry flight path angle). Day of departure from the Moon, trajectory inclination angle, and landing site are thus the prime variables. The maximum declination of the Moon was assumed to be 28.5° for the entire analysis.

The ground tracks calculated for each landing site were quantized with respect to day of departure from the Moon, and with respect to inclination angle relative to the Earth's equator. Integral days of departure throughout the lunar month were taken, except at the node. Days are referred to either Northern or Southern Lunstice (NL or SL, respectively). Thus, consecutive computing points are at SL, SL + 1, SL + 2, SL + 3, SL + 4, SL + 5, SL + 6, Node, NL - 6, NL - 5, etc. The times corresponding to the node are approximately 6-3/4 days from the lunstices, equivalent to a 27-Earth-day lunar month. Inclination angles were varied in 5° steps (with a few exceptions).

Reentry points and ground tracks are identical for departures on the same day from lunstice, regardless of whether that day is before or after lunstice. This follows since the declination of the Moon is the same in both cases. Thus all tracks are labeled with ± signs for the day of departure.

Figures 3-2 through 3-7 show representative ground tracks for pre-reentry trajectories terminating at the following assumed landing sites:

Figure 3-2:	Southwestern U.S., (near San Antonio)	Latitude 29.5°N,	Longitude 99°W
Figure 3-3:	Woomera, Australia,	Latitude 29.5°S,	Longitude 135°E
Figure 3-4:	Pacific Ocean (near Hawaii)	Latitude 20°N,	Longitude 150°W
Figure 3-5:	Pacific Ocean (near Samoa)	Latitude 10°S,	Longitude 170°W
Figure 3-6:	Atlantic Ocean, (near Antigua)	Latitude 17°N,	Longitude 60°W
Figure 3-7:	Pacific Ocean (near Panama)	Latitude 0°,	Longitude 85°W

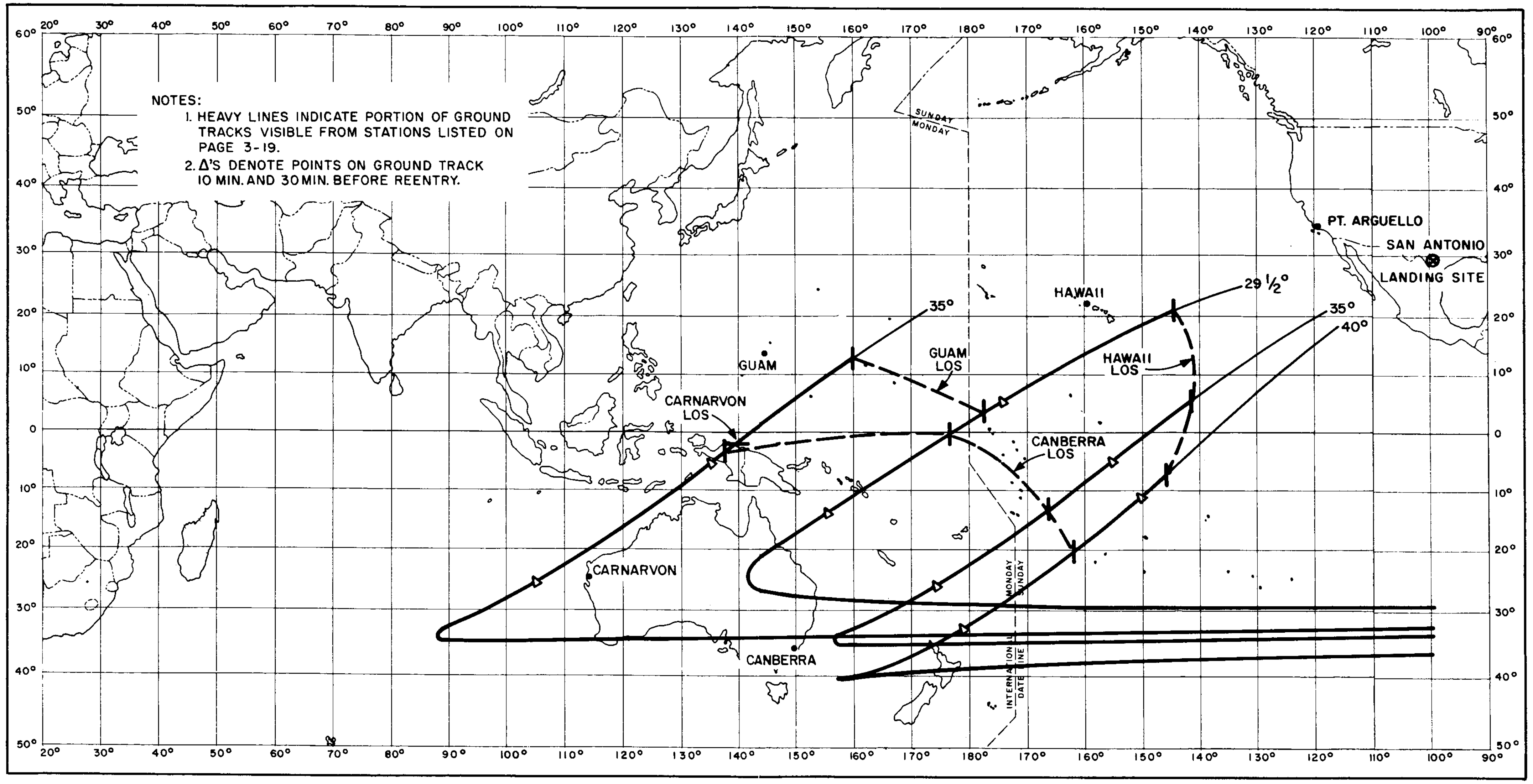

Figure 3-2. Pre-Reentry Tracks for San Antonio Landing

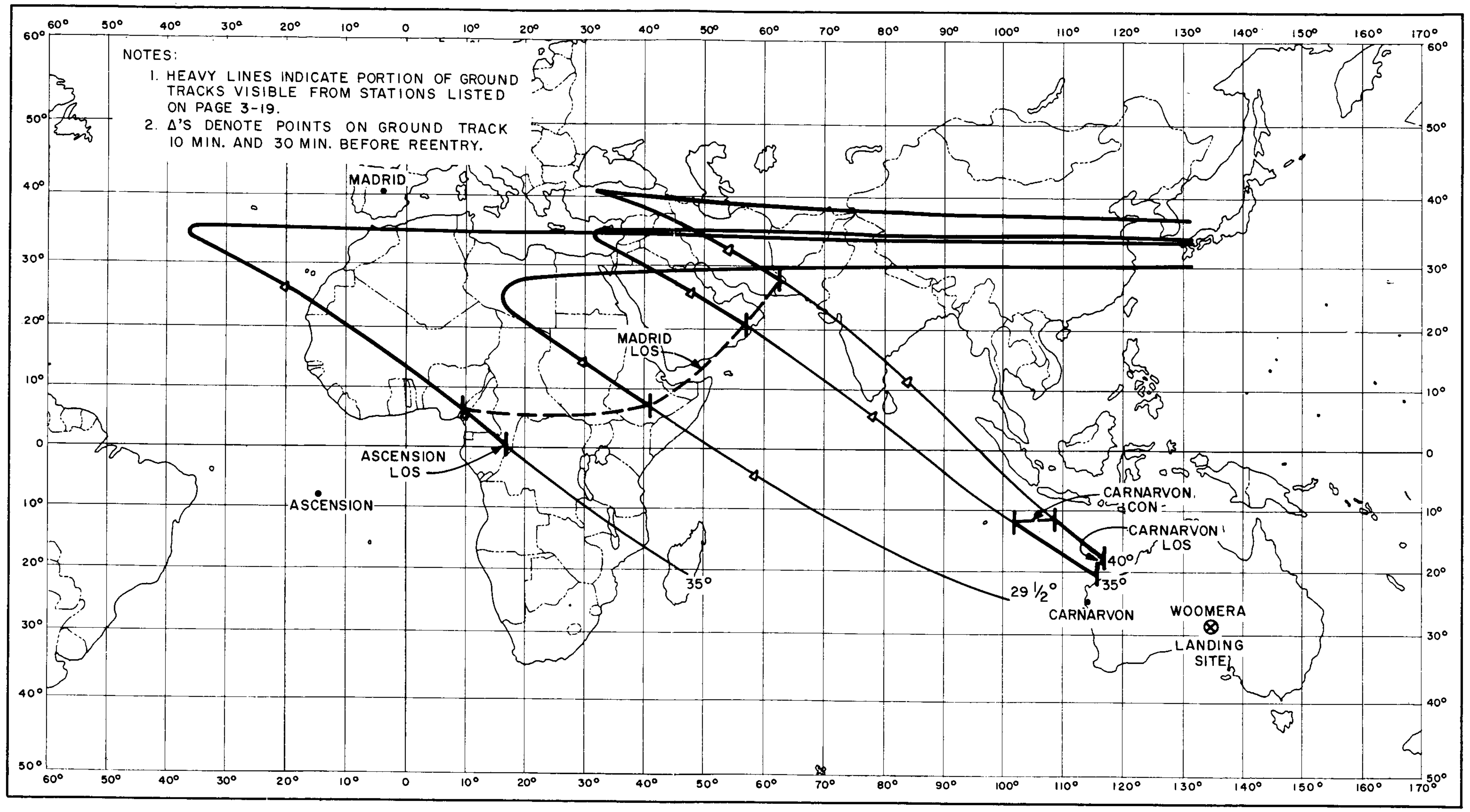

Figure 3-3. Pre-Reentry Tracks for Woomera Landing

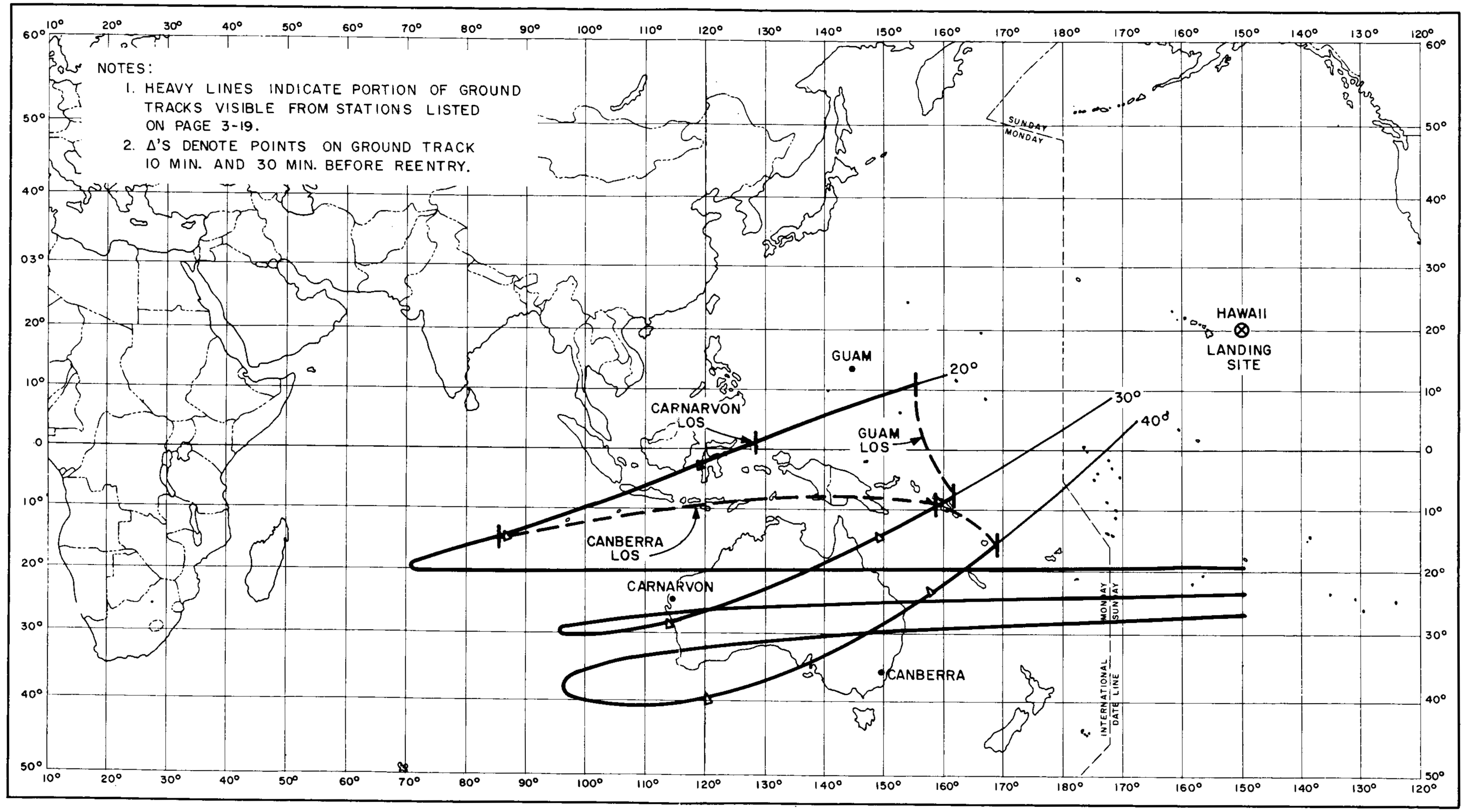

Figure 3-4. Pre-Reentry Tracks for Hawaii Landing

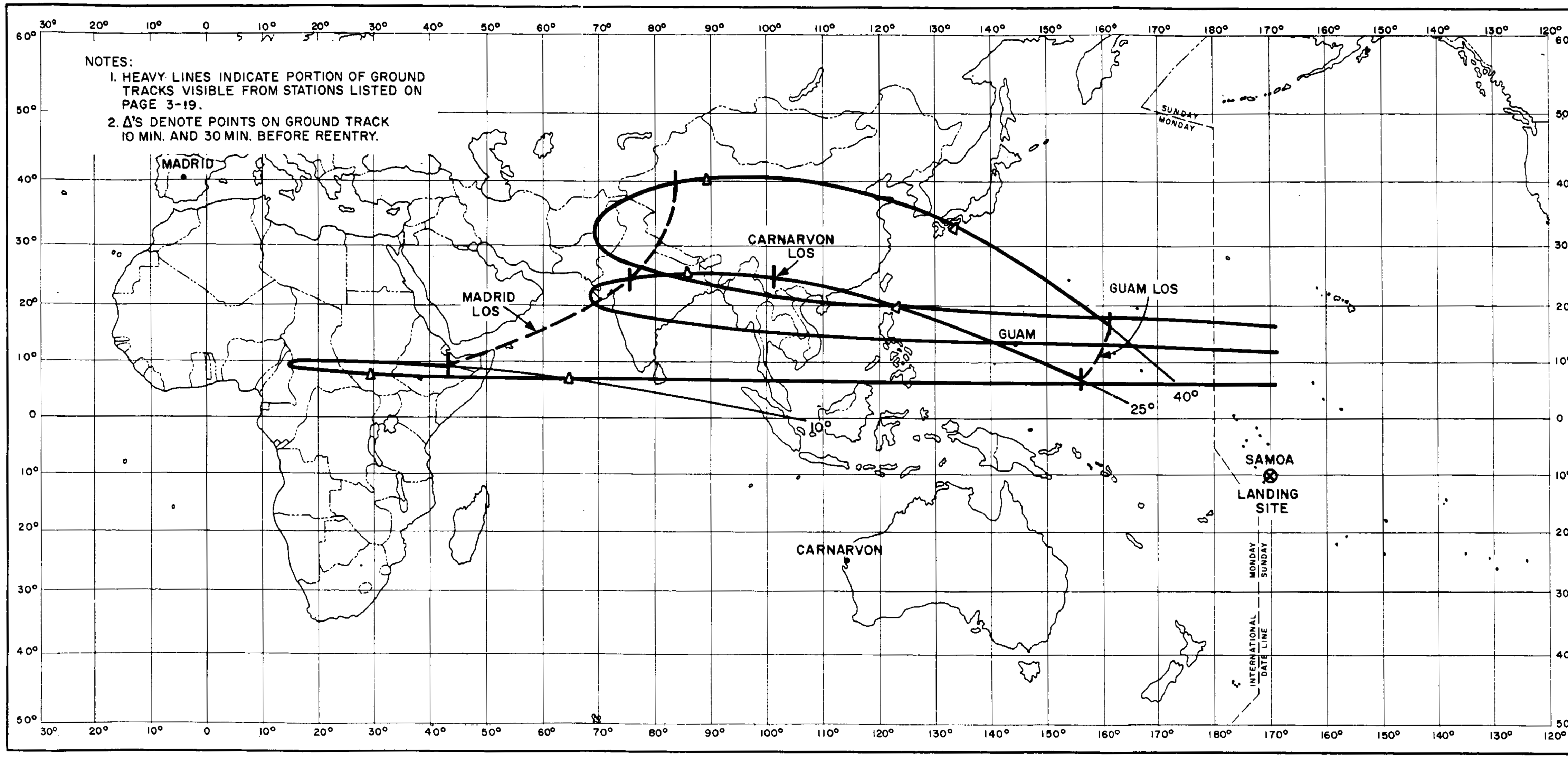

Figure 3-5. Pre-Reentry Tracks for Samoa Landing

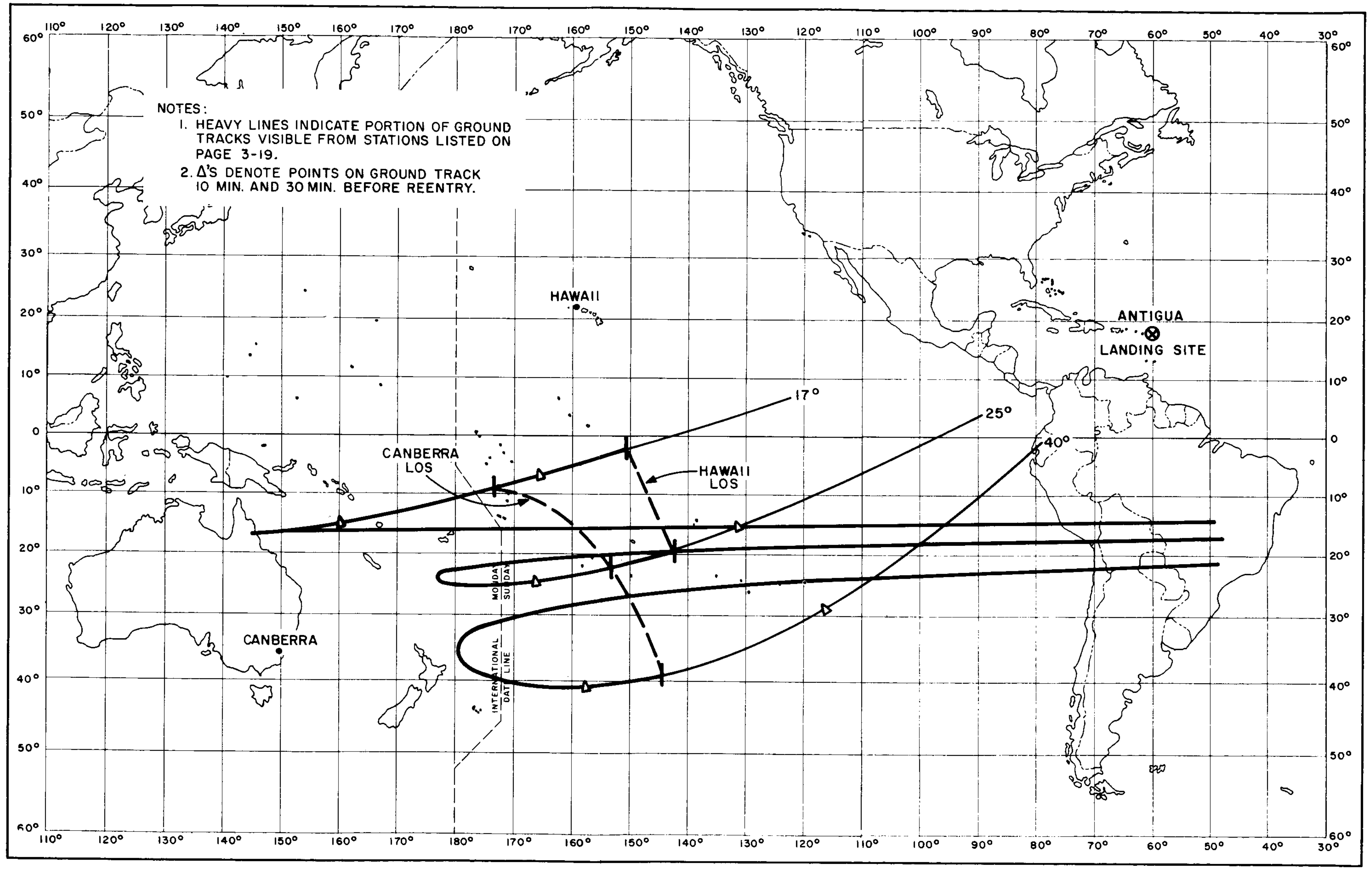

Figure 3-6. Pre-Reentry Tracks for Antigua Landing

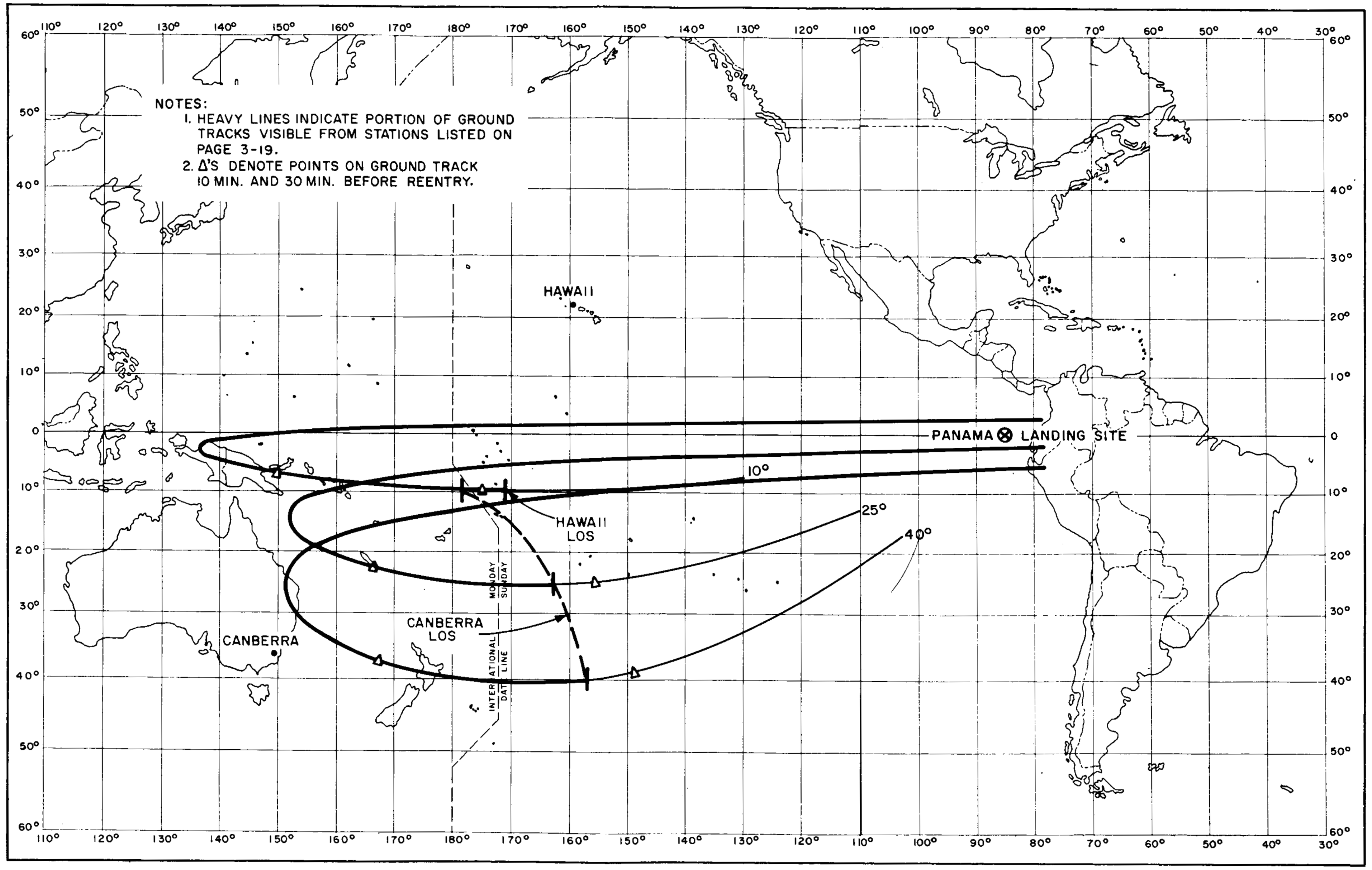

Figure 3-7. Pre-Reentry Tracks for Panama Landing

Tracks for two additional water landing sites — at ±10° latitude, 130° west longitude — have been computed but are not plotted here.

The tracks shown on each of Figures 3-2 through 3-7 are for different inclination angles but for the same day of departure from the Moon. In all cases, the tracks are terminated at the reentry points. The coverage limits for various ground stations as shown on the illustrations will be discussed later.

In line with assumptions 2 and 3 in the Introduction (page 1-3), ground tracks have been calculated for all days of the lunar month and for trajectory inclination angles up to a maximum of 40°. The minimum trajectory inclination in all cases is a value equal to the latitude of the intended landing site, or a value equal to the declination of the Moon on a given day of the month, whichever is greater. Thus, the only constraints imposed on trajectories and ground tracks for the various landing sites are those imposed by geometry. Conceivably, various mission constraints (e.g., fuel budgets) may ultimately impose further restrictions on the allowable sets of trans-Earth trajectories, and thereby ease the C&T coverage requirements; however, the specific constraints are not yet evident and hence there is no basis at this time for excluding from the coverage analysis any of the ground tracks developed here.

COVERAGE OF PRE-REENTRY TRACKS

The specific land stations assumed for the pre-reentry coverage analysis are the following:

Ascension Island

Carnarvon, Australia

Guam

Hawaii

Pt. Arguello, California

Corpus Christi, Texas

Goldstone
Madrid
Canberra } deep-space stations

Figure 3-8 shows the locations of the land stations listed above, together with several stations assumed later in the reentry coverage analysis. 10,000-mile visibility contours for selected stations are also shown.

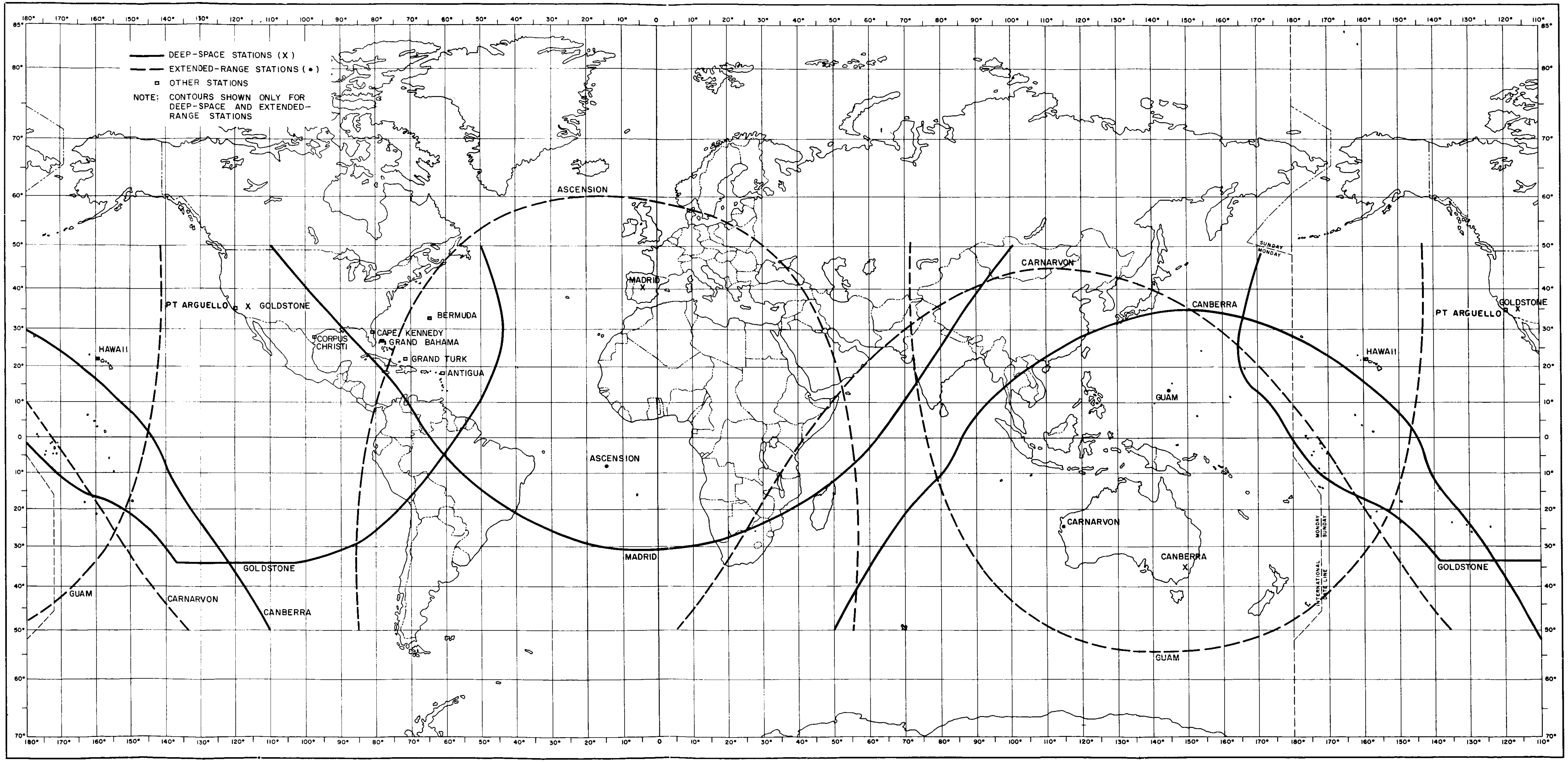

Figure 3-8. C&T Land Station Locations

Representative coverage capabilities of various C&T stations are indicated on Figures 3-2 through 3-7 by the heavy line portions of the ground tracks. Coverage data for these tracks, and for others which were computed but are not illustrated here, are shown in bargraph form in Figures 3-9 through 3-14. These charts show the time (in minutes before reentry) that the last deep-space station loses contact with the spacecraft. In a few cases, there is a gap in the coverage provided by the deep-space stations prior to the final loss of visibility by a deep-space station. The charts also show loss of visibility times for other stations that are capable of supplementing the coverage of the deep-space stations. In most instances, this supplementary coverage occurs after loss of visibility by the deep-space station; in a few cases, however, an earlier gap in the coverage of the deep-space network can be filled by a non-deep-space station. The entries in the column at the right of each chart show the total out-of-contact time for the trajectory being considered, provided that each station having visibility of the spacecraft during that trajectory also has the required range capability to do something about it. Range requirements for the various stations are discussed in the next section.

The objective of communicating and tracking during and after the last mid-course correction can be met by the deep-space stations for all tracks terminating at San Antonio, Woomera, Antigua, and Panama. At least 13 minutes of continuous coverage can always be provided for trajectories to these sites, even though the last mid-course correction occurs as late as one hour before reentry. Coverage by the deep-space stations cannot be guaranteed for 48% of the Hawaii tracks and for 20% of the Samoa tracks, if the last mid-course correction can occur at any time between one and three hours before reentry. However, all tracks to the latter sites can be covered continuously for at least 16 minutes after the mid-course correction by using the Carnarvon and Guam stations.

The ability to realize the objective of communicating and tracking for 5 minutes following the jettisoning of the SM is indicated in Table 3-1. This table shows the percentages of tracks for which this objective can be met, assuming the use of both the deep-space and shorter-range stations listed on page 3-5.

Table 3-2 below shows the results of averaging the coverage data for all tracks. The first entry for each landing site gives the average time, in minutes before reentry, when continuous deep-space coverage is lost. The second entry gives the average deep-space station out-of-contact time. It differs from the first entry when there are gaps in the deep-space coverage. The last entry gives the average out-of-contact time when near-Earth stations are added to supplement the deep-space coverage.

Table 3-1

PERCENTAGE OF TRAJECTORIES WITH AT LEAST FIVE MINUTES OF C&T AFTER SM SEPARATION

Landing Site	Time Between SM Separation and Reentry 30 Min.	20 Min.	10 Min.
San Antonio	100	100	24
Woomera	100	58	0
Hawaii	100*	98*	74*
Samoa	98*	66*	66*
Antigua	100	84	30
Panama	100	100	53

*Considered as paired sites, with landings at Hawaii for "SL" through the "Node" day, and at Samoa for the balance of the month, the percentages of all trajectories covered are:

For separation at 30 Min.: 100%
For separation at 20 Min.: 97%
For separation at 10 Min.: 81%

Table 3-2

AVERAGE OUT-OF-CONTACT TIME

Landing Site	Average Time Before Reentry for Loss of Continuous Deep-Space Coverage (Minutes)	Average Deep-Space Station Out-of-Contact Time (Minutes)	Average Combined Deep-Space and near-Earth Station Out-of-Contact Time (Minutes)
San Antonio	9.3	9.3	6.6
Woomera	13.7	13.7	13.4
Hawaii	75.7	67.0	4.4
Samoa	50.4	39.6	11.2
Antigua	13.2	11.2	8.6
Panama	17.6	16.0	5.3

Note that the Hawaii landing site, which has the earliest average deep-space loss-of-signal time, has the least total out-of-contact time when near-Earth sites are included. Near-Earth station coverage is also very useful in reducing the out-of- contact time for Samoa, and moderately useful for the equatorial site near Panama. It is less useful for San Antonio and Antigua, but supplementary coverage is not particularly needed for these two landing sites since they have the latest deep-space LOS times. Near-Earth coverage is least useful for Woomera, providing an average of only 0. 3 minutes additional coverage. (Most of Woomera's out-of-contact time occurs over the Indian Ocean, and could be reduced by ship stations. This will be discussed later in this section.)

The specific stations providing useful pre-reentry coverage are shown in Table 3-3. The column on the left shows the average deep-space station out-of-contact time. The next six columns show the average reduction in out-of-contact time provided by each station that is useful for this purpose. These stations are considered independently. Thus, the total out-of-contact time shown in the far right column cannot in general be derived by subtracting the total reduction for all near-Earth stations from the deep-space station out-of-contact time. It is assumed the stations are not range limited. In the cases of Carnarvon and Guam, the range required is substantial (see the following section entitled, PRE-REENTRY RANGE REQUIREMENTS).

Details on the coverage for each track considered are given in Figures 3-9 through 3-14. Each track is identified as to day of departure, trajectory inclination, and landing approach heading. The upper bar(s) on each track show the deep-space coverage. The lower bar(s) shows the near-Earth coverage starting at the time of loss of continuous deep-space coverage. In order to keep these graphs readable and relatively compact, no attempt has been made to show overlap in station coverage (except for deep-space and near-Earth station overlap when the near-Earth station can cover an early gap in deep-space contact).

Pre-reentry coverage for two additional landing sites has been examined (10°N, 130°W, and 10°S, 130°W). These sites were chosen specifically to explore the reentry coverage that might be provided by ship C&T stations, as discussed in Section 4. Pre-reentry coverage data was generated for these sites, but was not plotted because the general pre-reentry coverage characteristics are similar to those for Hawaii and Samoa. The earliest loss of continuous deep-space coverage was about 3-1/2 hours before reentry for both sites, and the average deep-space station out-of-contact time for both sites was substantial. Carnarvon and Guam appeared to be very useful stations for reducing the out-of-contact time.

Table 3-3

AVERAGE REDUCTION IN OUT-OF-CONTACT TIME (IN MINUTES) USING NEAR-EARTH STATIONS

Landing Site	Average Deep-Space Out-of-Contact Time	Average Reduction in Out-of-Contact Time for Near-Earth Stations at:						Average Out-of-Contact Time With Near-Earth Stations Included
		Carnarvon	Guam	Hawaii	Ascension	Pt. Arguello	Corpus Christi	
San Antonio	9.3	0.0+	0.6	2.1	---	---	---	6.6
Woomera	13.7	0.2	---	---	0.2	---	---	13.4
Hawaii	67.0	56.8	16.3	---	15.7	---	---	4.4
Samoa	39.6	24.2	9.0	---	---	---	---	11.2
Antigua	11.2	---	---	2.1	---	0.7	0.4	8.6
Panama	16.0	0.8	7.7	8.6	---	0.7	---	5.3

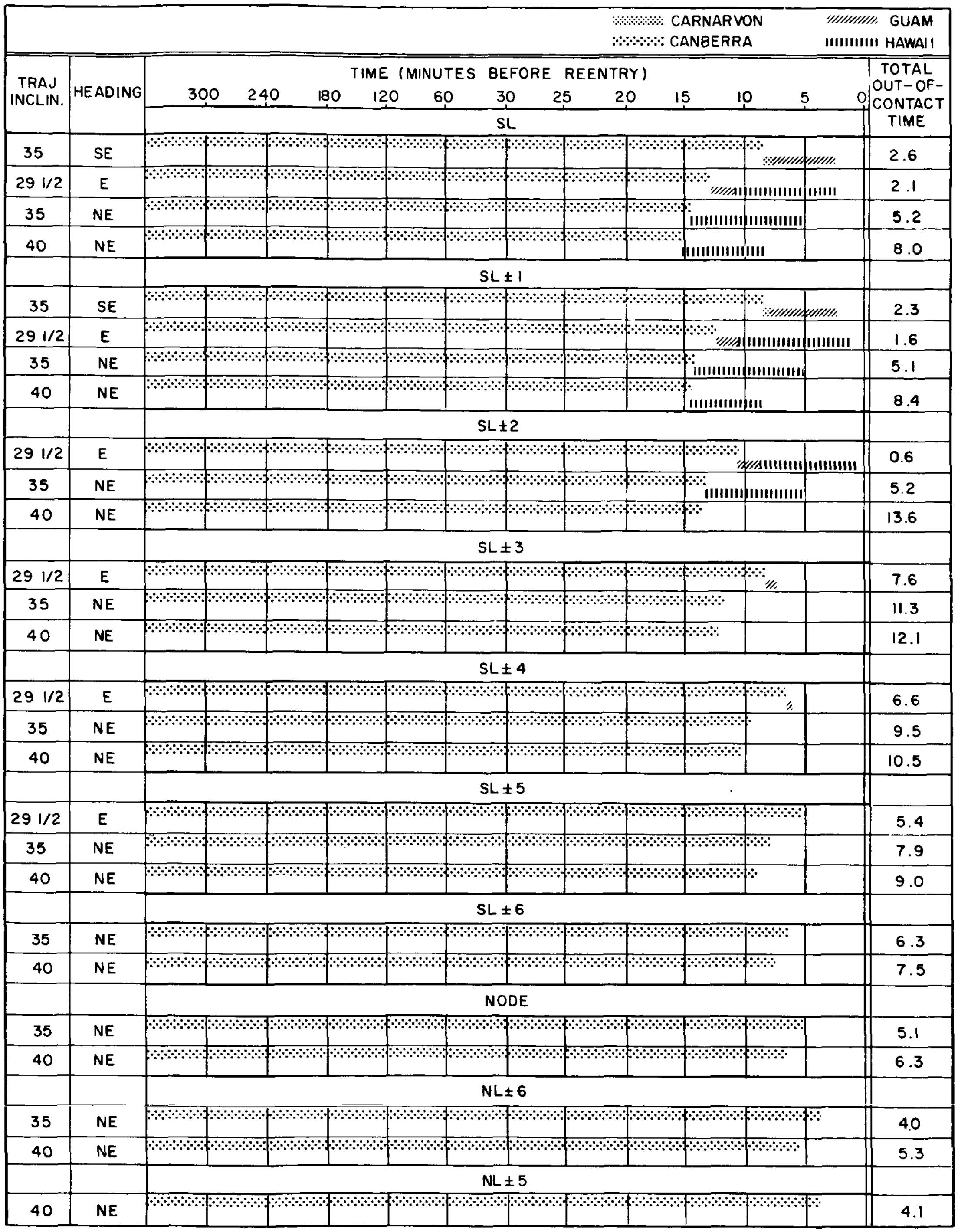

Figure 3-9. Pre-Reentry Coverage for San Antonio Landing

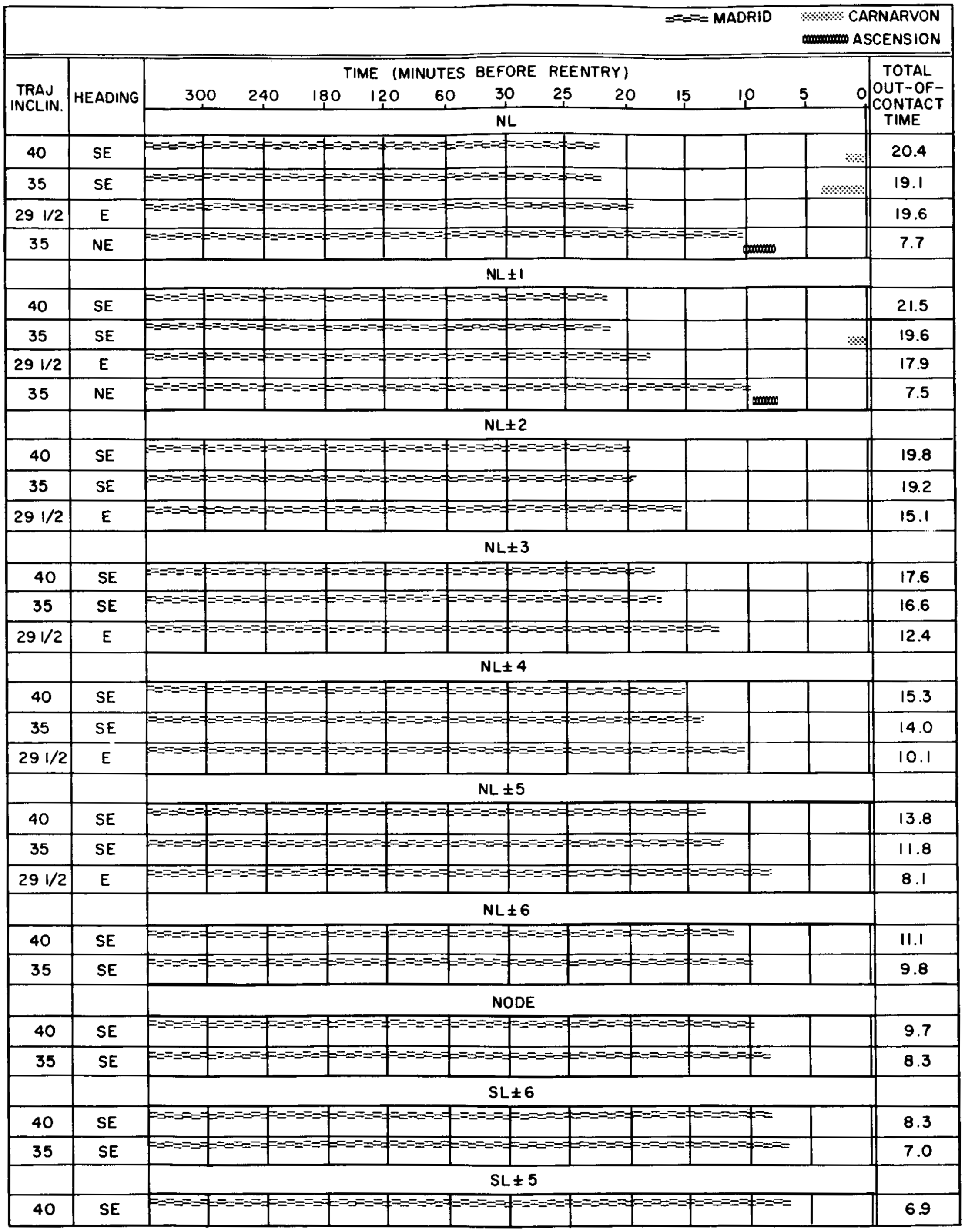

Figure 3-10. Pre-Reentry Coverage for Woomera Landing

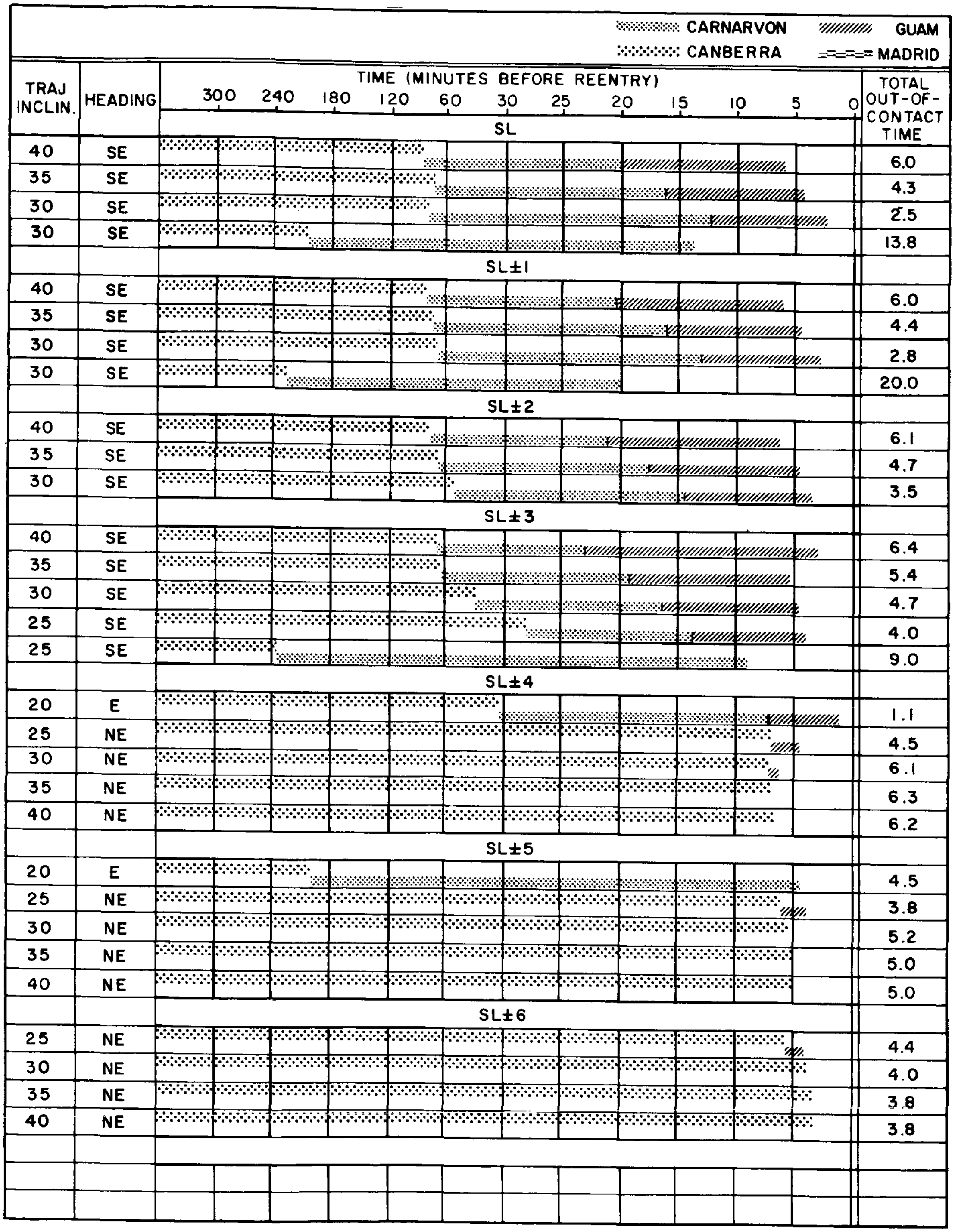

Figure 3-11. Pre-Reentry Coverage for Hawaii Landing (sheet 1)

CARNARVON GUAM
CANBERRA MADRID

TRAJ INCLIN.	HEADING	TIME (MINUTES BEFORE REENTRY) 300 240 180 120 60 30 25 20 15 10 5 0	TOTAL OUT-OF-CONTACT TIME
		NODE	
25	NE		3.4
30	NE		3.4
35	NE		2.9
40	NE		2.9
		NL±6	
25	NE		2.0
30	NE		3.4
35	NE		2.1
40	NE		2.1
		NL±5	
30	NE		2.0
35	NE		1.4
40	NE		1.1
		NL±4	
35	NE		2.2
40	NE		0.2
		NL± 3	
40	NE		1.0

Figure 3-11. Pre-Reentry Coverage for Hawaii Landing (sheet 2)

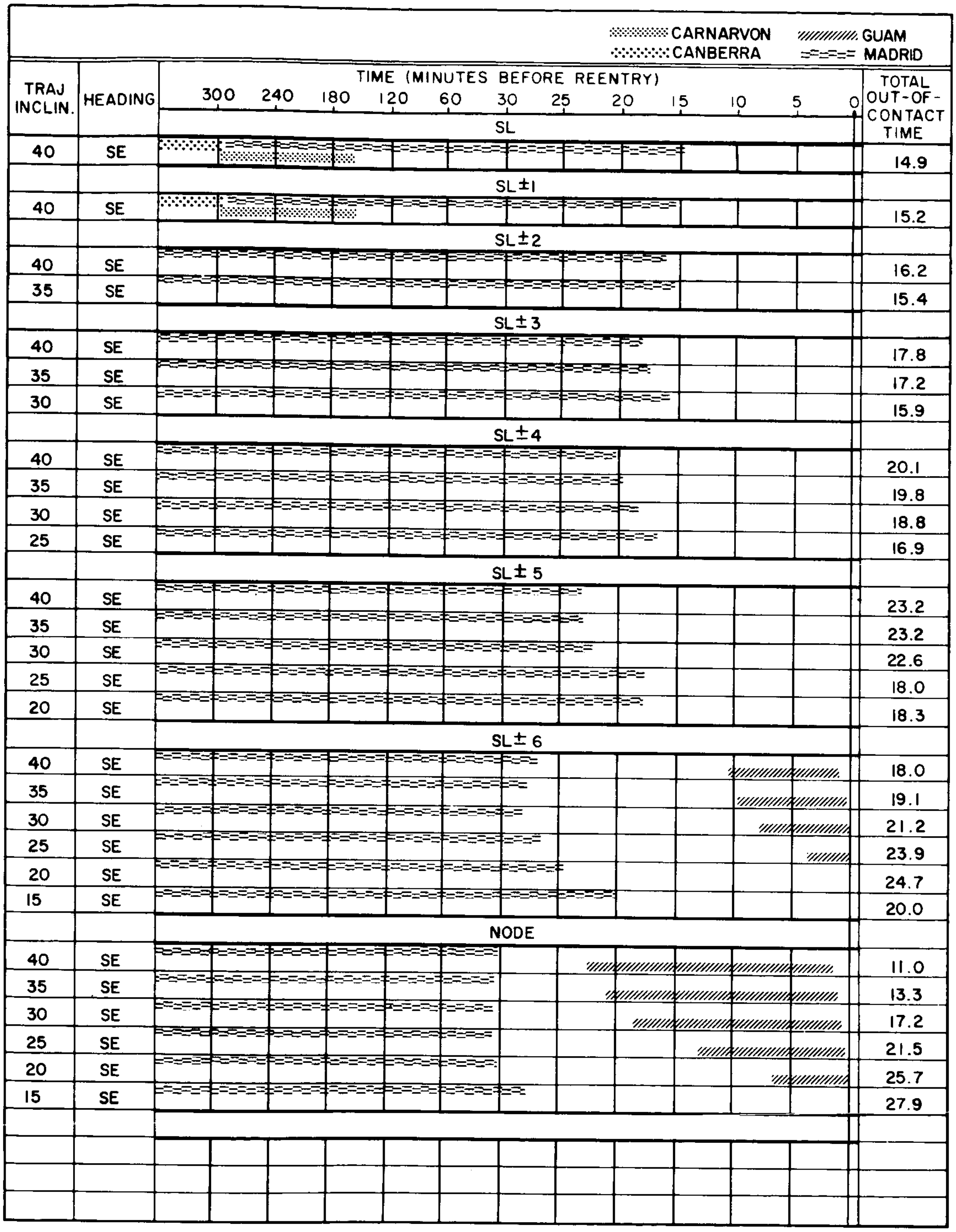

Figure 3-12. Pre-Reentry Coverage for Samoa Landing (sheet 1)

CARNARVON GUAM
CANBERRA MADRID

TRAJ INCLIN.	HEADING	TIME (MINUTES BEFORE REENTRY) 300 240 180 120 60 30 25 20 15 10 5 0	TOTAL OUT-OF-CONTACT TIME
		NL ± 6	
40	SE		2.6
35	SE		2.3
30	SE		2.0
25	SE		1.7
20	SE		1.5
15	SE		1.4
10	E		19.3
		NL ± 5	
15	NE		4.0
20	NE		2.9
25	NE		2.5
30	NE		2.3
35	NE		2.2
40	NE		2.1
		NL ± 4	
20	NE		2.9
25	NE		1.5
30	NE		1.1
35	NE		1.0
40	NE		1.1
		NL ± 3	
25	NE		1.7
30	NE		0.3
35	NE		0.0
40	NE		0.2
		NL ± 2	
30	NE		8.5
35	NE		0.5
40	NE		0.0
		NL ± 1	
30	NE		19.5
35	NE		2.9
40	NE		0.7
		NL	
30	NE		20.9
35	NE		12.2
40	NE		1.5

Figure 3-12. Pre-Reentry Coverage for Samoa Landing (sheet 2)

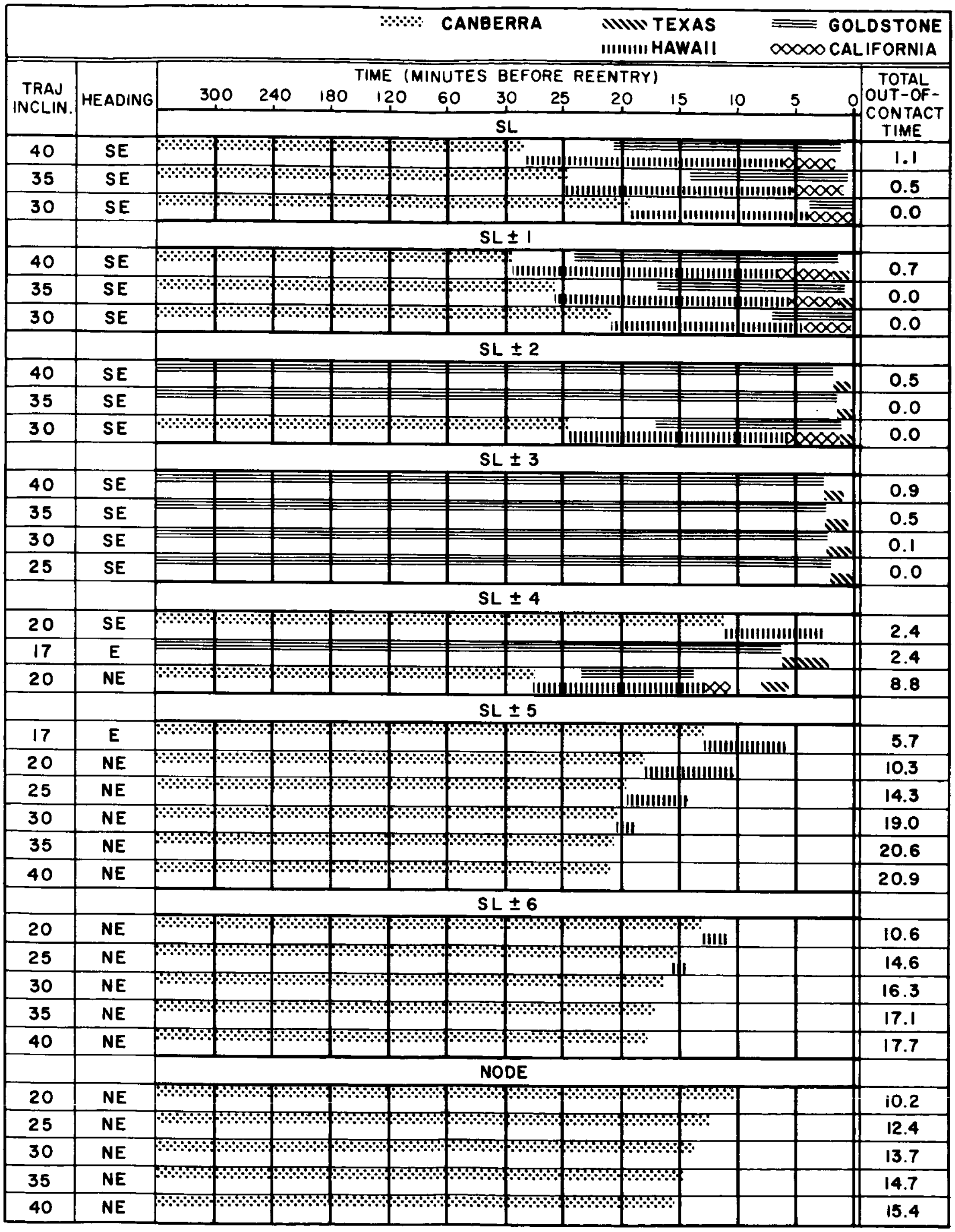

Figure 3-13. Pre-Reentry Coverage for Antigua Landing (sheet 1)

CANBERRA — TEXAS — GOLDSTONE — HAWAII — CALIFORNIA

TRAJ INCLIN.	HEADING	TIME (MINUTES BEFORE REENTRY) 300 240 180 120 60 30 25 20 15 10 5 0	TOTAL OUT-OF-CONTACT TIME
		NL ± 6	
25	NE		10.1
30	NE		11.6
35	NE		12.6
40	NE		13.4
		NL ± 5	
25	NE		7.7
30	NE		9.3
35	NE		10.5
40	NE		11.4
		NL ± 4	
30	NE		7.4
35	NE		8.7
40	NE		9.7
		NL ± 3	
35	NE		7.3
40	NE		8.4
		NL ± 2	
40	NE		7.4

Figure 3-13. Pre-Reentry Coverage for Antigua Landing (sheet 2)

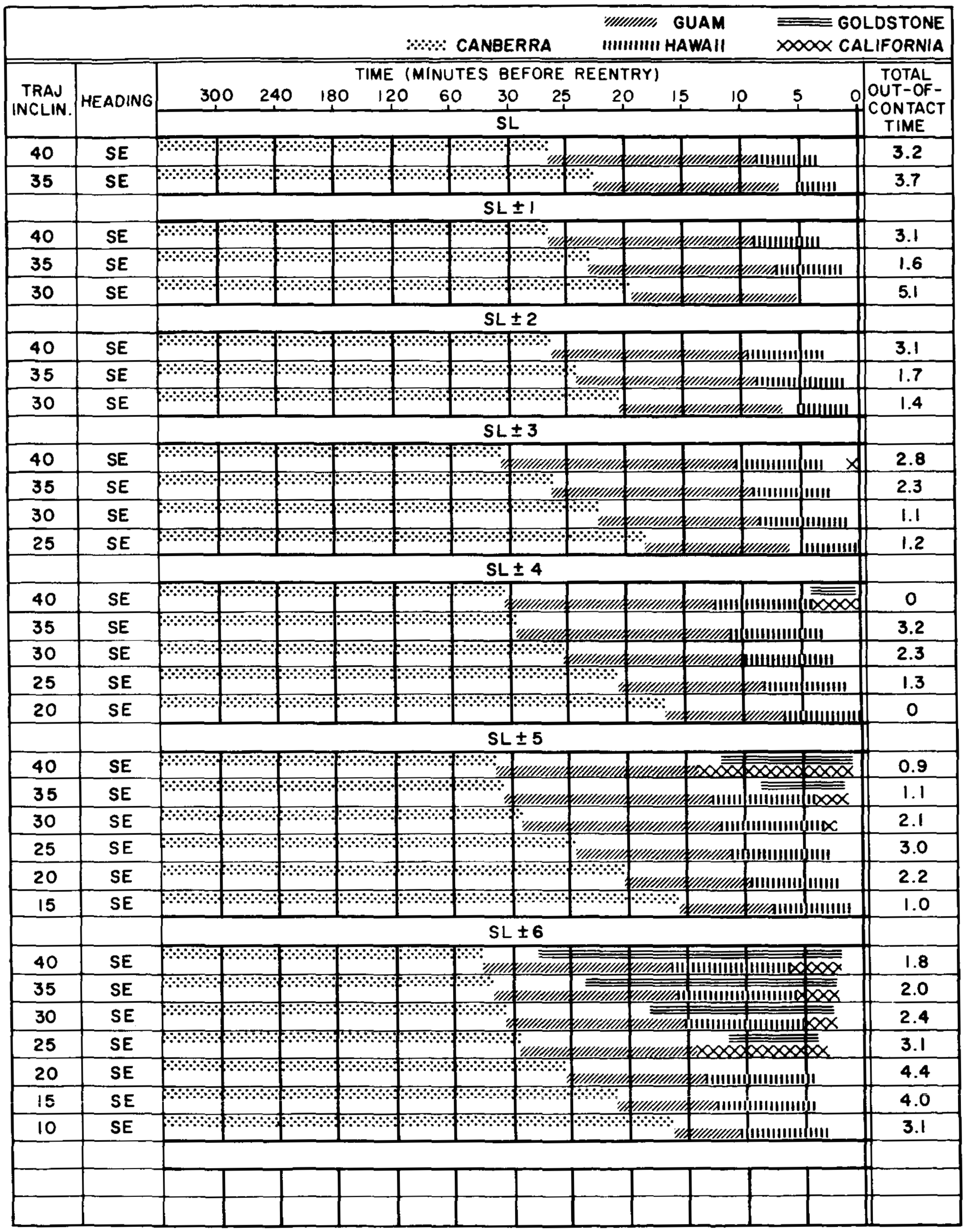

Figure 3-14. Pre-Reentry Coverage for Panama Landing (sheet 1)

GUAM — GOLDSTONE — CANBERRA — HAWAII — CALIFORNIA

TRAJ INCLIN.	HEADING	TIME (MINUTES BEFORE REENTRY) 300 240 180 120 60 30 25 20 15 10 5 0	TOTAL OUT-OF-CONTACT TIME
		NL ± 6	
10	NE		9.0
15	NE		12.1
20	NE		12.4
25	NE		12.4
30	NE		12.4
35	NE		12.4
40	NE		12.5
		NL ± 5	
15	NE		7.8
20	NE		9.0
25	NE		9.7
30	NE		10.1
35	NE		10.3
40	NE		10.6
		NL ± 4	
20	NE		6.1
25	NE		7.3
30	NE		8.1
35	NE		8.6
40	NE		9.0
		NL ± 3	
25	NE		5.2
30	NE		6.4
35	NE		7.1
40	NE		7.7
		NL ± 2	
30	NE		4.9
35	NE		6.0
40	NE		6.7
		NL ±1	
30	NE		3.9
35	NE		5.2
40	NE		6.1
		NL	
35	NE		5.0
40	NE		5.9

Figure 3-14. Pre-Reentry Coverage for Panama Landing (sheet 2)

The chief problems in providing pre-reentry coverage are the range requirements at Carnarvon and Guam for covering Hawaii and Samoa landings. Range requirements are discussed in the next section entitled, PRE-REENTRY RANGE REQUIREMENTS. In an effort to see whether these range requirements might be reduced, the coverage capabilities of the Johannesburg deep-space site (part of the DSIF) were analyzed for Hawaii and Samoa landings. All of the very early deep-space LOS's occur when the spacecraft is over the Indian Ocean, approximately equidistant from both Madrid and Canberra. The tracks corresponding to these early LOS's all pass near Johannesburg.

If Johannesburg is considered along with Canberra, Madrid, and Goldstone, the earliest deep-space station LOS is 63 minutes for Hawaii landings and 45 minutes for Samoa landings. In all cases, Johannesburg's coverage extends back several hours in time so that no gaps are introduced in the deep-space coverage prior to final deep-space LOS.

Reference 5 has suggested the possibility of one or two ships in the Indian Ocean to provide tracking coverage after the trans-lunar injection. The possible use of one of these ships for pre-reentry coverage as well has been studied. It was found that if the ship is stationed in the western area of the Indian Ocean, it can fill the gaps in deep-space station coverage of Madrid and Canberra for landings at Hawaii and Samoa. Thus, three possibilities of covering these gaps are apparent: provide adequate range capability at Carnarvon (32,100 miles is cited later), use the Johannesburg deep-space station (or some other land station in that vicinity with about 32,000-mile range capability), or use a ship in the western part of the Indian Ocean. It is worth noting that the spacecraft altitude when passing over the Indian Ocean and headed for landings at Hawaii or Samoa is so high that it is very little different from the slant range to any C&T station at the limit of visibility. In other words, the range that would be required for a ship positioned directly underneath the spacecraft would be almost as much as the range required at a ground station (e.g., Carnarvon) several thousand miles away.

The use of a ship to provide pre-reentry coverage for landings at Woomera has also been studied. In this case, the spacecraft altitude over the Indian Ocean is relatively low as it approaches Australia, and the spacecraft does not become visible to Carnarvon until it gets near the Australian West Coast. Figure 3-10 indicates that the earliest loss of contact by a deep-space station (Madrid) is about 22 minutes before reentry, and that there are a number of trajectories for which the subsequent out-of-contact times are of the order of 20 minutes. The average out-of-contact time, without including ships, is about 13.4 minutes.

To determine how well ships might supplement this coverage, fifteen arbitrary ship locations in the Indian Ocean were chosen for analysis, and the reduction in the average out-of-contact time was calculated independently for each location. Figure 3-15 shows these locations and the percentage reduction in out-of-contact time associated with each for landings at Woomera. It is apparent from this figure that the optimum location for a single ship for extending pre-reentry coverage is in the northern area of the Indian Ocean. Also shown are three possible ship locations examined in Reference 5 for possible coverage of other mission phases. The arcs drawn from these locations show the re-deployment radius possible for these ships with seven days of sailing time at a speed of ten knots.

PRE-REENTRY RANGE REQUIREMENTS

Consistent with the objectives stated in Section 1 and the general approach followed throughout this section, the only stations to be considered for pre-reentry coverage are stations which also have a role in the earlier Earth orbit and/or post-injection phases of the Apollo mission. It will be assumed that the C&T functions to be performed during the pre-reentry interval are the same as during these earlier phases; specifically, they will include tracking, two-way voice, spacecraft-to-ground telemetry, and ground-to-spacecraft data transmission. Assuming also that channel capacities, signal frequencies, and modulation methods are the same, stations active during the pre-reentry interval should need no additional radio or baseband terminal equipments. Larger antennas may or may not be required, depending on whether a station is one that has been planned only for service while the spacecraft is in the Earth parking orbit, or may have been given an extended range capability to cover the post-injection phase as well.

The desired range capabilities for various stations during the pre-reentry period are indicated in Table 3-4. This table has been prepraed from the same trajectory data used in plotting the various ground tracks and station coverage capabilities shown elsewhere in this section. The criteria used in developing the entries listed in the table are illustrated in Figure 3-16. Here, ground tracks are shown for two typical trajectories terminating at a landing site near Hawaii. The tracks differ in the inclination angle and reentry path length involved. Also shown are the limits of visibility (at 5° above the horizon) for the deep-space station at Canberra and an assumed station at Guam. In Case A, the coverages partially overlap. For purposes of determining the appropriate range entry in Table 3-4, the required range for the Guam station is taken only as the range to the point where Canberra loses visibility. In those cases where the overlap of coverage by a deep-space site and a non-deep-space site is considerable, choice of the visibility limit from the non-deep-space site as the criterion for setting a range requirement would be unnecessarily demanding.

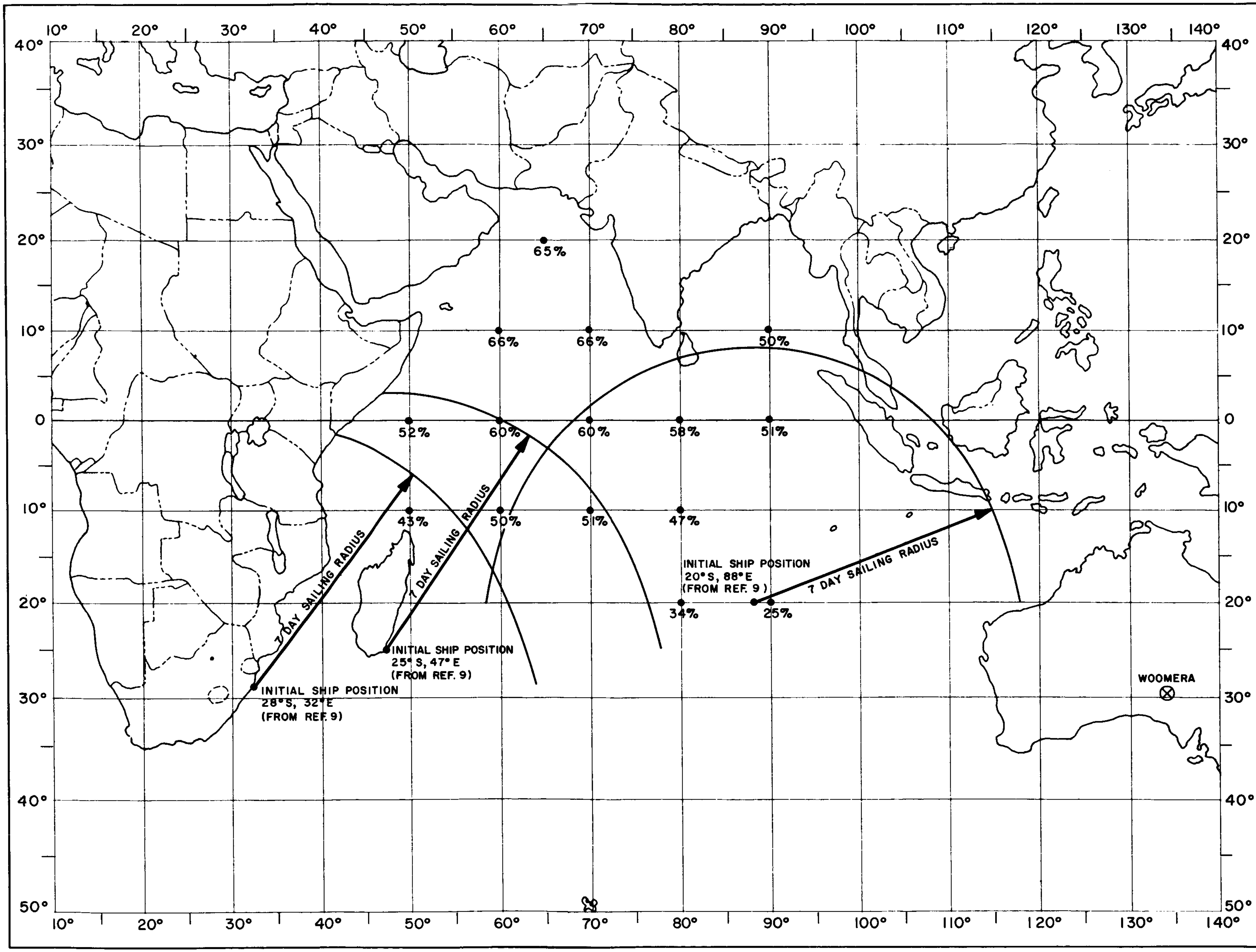

Figure 3-15. Indian Ocean Ship Locations Assumed for Pre-Reentry Coverage Analysis, Woomera Landing

For some trajectories, represented by Case B in Figure 3-16, there is no overlap of coverage between a deep-space site and the non-deep-space site of interest. In these cases, the range requirement is taken to be that represented by the visibility limit, in order to provide coverage of as much of the trajectory as possible. The entry listed in Table 3-4 for a particular combination of C&T station and landing site is the maximum range found by considering all cases of types A and B among the trajectories discussed in Section 4.

There are some cases, particularly for Hawaii and Samoa landings, where gaps occur in deep-space coverage well before reentry (up to 5 hours in the worst case). Generally, the gaps are brief. In all cases, a near-Earth station (usually Carnarvon) can cover these gaps. However, when the gaps were less than 5 minutes in duration and would have required a longer range of the near-Earth station than would otherwise be required, they were ignored. It is presumed that if a mid-course correction were planned for a time when there was such a coverage gap, it could be re-scheduled a few minutes earlier or later at a time when coverage is available. Without such an assumption, the range requirement for Carnarvon would be 38,700 nm (for a Samoa landing). Range requirements would be increased slightly for some other cases, but not more than 20 to 25%.

Table 3-4 considers the stations to be operating co-operatively (e.g., if two stations can both provide coverage at a long range, the long range requirement is assigned to only one of them). If the stations had been considered independently, Guam, in particular, would have required a much longer range (over 30,000 nm).

Table 3-4

SUMMARY OF RANGE REQUIREMENTS FOR NON-DEEP-SPACE STATIONS PRIOR TO REENTRY

	Slant Range (nm) Required for Landing at:					
C&T Station	San Antonio	Woomera	Hawaii	Samoa	Antigua	Panama
Carnarvon	2,400	1,100	32,100*	26,700*	---	---
Guam	3,000	---	4,600	8,700	---	7,800
Hawaii	3,700	---	---	---	5,300	2,200
Ascension	---	2,200	---	---	---	---
Pt. Arguello	---	---	---	---	3,300	1,200
Corpus Christi	---	---	---	---	2,200	---

*Carnarvon's range can be reduced to 4000 nm for Hawaii and 7000 nm for Samoa if the Johannesburg deep-space station can be used.

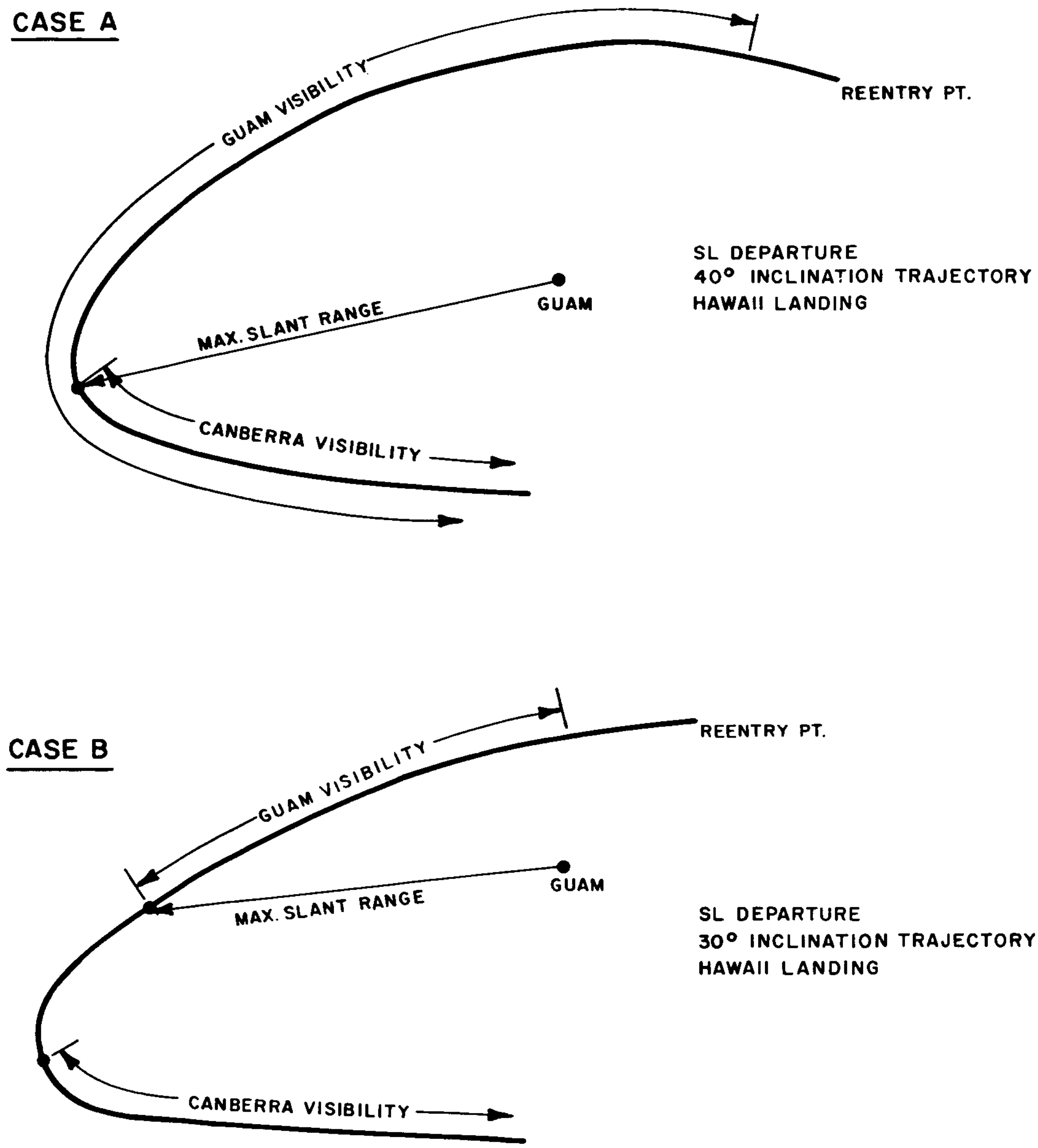

Figure 3-16. Range Requirements for Non-Deep-Space Stations Prior to Reentry

The range at the time of jettisoning the SM is of special interest, because at this time the directional antenna on the SM is lost. From then on, a non-directional antenna on the CM must be used. The longest range from a ground station at which the jettisoning can occur is 6, 700 nm, if this event occurs 30 minutes before reentry and the spacecraft is then at the limit of visibility for a 5° masking angle. The shortest range (also for 30 minutes) is 4, 575 nm, applying when the CM-SM separation occurs directly over the ground station. Ranges at or very near the maximum of 6700 miles are required at Carnavon for landings at Hawaii and Samoa, and at Guam for landings at Samoa and the equatorial site near Panama. For all other combinations of landing sites and C&T stations, the maximum ranges, as indicated in Table 3-4, occur after the CM-SM separation if this event occurs as early as 30 minutes before reentry.

Section 4

REENTRY COVERAGE

This section is concerned with communication and tracking coverage during the reentry phase of an Apollo return flight from the Moon. The period of interest extends from the time that the spacecraft first reaches 400,000 feet altitude until landing.

The approach followed in this section generally parallels that of the preceding section on pre-reentry coverage, except that a discussion of the objectives for reentry coverage will be deferred until after the reentry trajectory and ground track characteristics have been described. This is done because of the major impact that these characteristics have on the specific objectives ultimately adopted for the reentry coverage analysis.

REENTRY GROUND TRACKS AND ALTITUDE PROFILES

As in the case of the pre-reentry coverage analysis, the intent here is to place no restrictions on mission flexibility, other than those restrictions explicitly or implicitly contained in the assumptions stated in the Introduction, Section 1. The principal assumptions affecting considerations here include the limitation on trajectory inclination angle to a maximum of 40° relative to the Earth's equator, and the limitation on reentry range to values between 1200 and 5000 nautical miles. These assumptions serve to define areas on the surface of the Earth covered by sets of ground tracks to specific landing points. As in Section 3, the maximum declination of the Moon is taken as 28.5° throughout.

Reentry Ground Tracks

Figures 4-1 through 4-6 show reentry ground tracks for the same landing sites illustrated in the pre-reentry study of Section 3. Details of the method of generating these tracks are described in Appendix B.

Figure 4-1 illustrates reentry tracks for a landing on the equator. The tracks on Figure 4-2 are drawn for a landing near Samoa, but can also be used for any other site at -10° latitude by an appropriate shift of the entire set of tracks in longitude. The tracks for a +10° latitude landing would be the mirror image of this set, the trajectories for days toward NL having a spread equal to that of the SL days for the -10° site. Figure 4-3 illustrates the ground tracks for landings at a +20° latitude site near Hawaii; again, the tracks for a -20° latitude landing would be the mirror image of this set. Figures 4-4 and 4-5 apply to landings at ±29.5° latitude — San Antonio and Woomera, respectively — while Figure 4-6 illustrates tracks for a site near Antigua.

The solid lines on these illustrations indicate the ground tracks for various trajectory inclination angles. The dashed lines are loci of reentry points for the indicated days of spacecraft departure from the Moon: SL, SL ± 1, etc. The tracks are bounded by a maximum inclination of 40° and the maximum range limit of 5000 nm. The minimum range of 1200 nm is also indicated on each illustration. All trajectories for which these ground tracks are drawn were computed for a nominal reentry flight path angle of -6.4°.

For each trajectory inclination and landing approach heading, there are two, one, or no possible reentry points on a given day. If the inclination exceeds the magnitude of the latitude of the landing site, two reentry points are theoretically possible. In almost all cases, at least one of these points requires a reentry range either longer than 5000 miles or shorter than 1200 miles and must be rejected. For a few cases, both reentry points are allowable (see Figure 4-3, the map for a Hawaii landing for some examples). For still other cases, neither reentry point is allowable. There will also be no reentry point along a given inclination trajectory if the declination of the Moon on the day of departure exceeds that particular trajectory inclination.

It is evident from the reentry track illustrations that an equatorial landing site permits greater flexibility in return trajectories in terms of allowable landing dates and trajectory inclinations than a site at any other latitude, under the assumption that fuel budget is not a limiting factor. As shown on Figure 4-1, all days of the month and all inclination angles from 0° to the maximum of 40° are represented. (The full spread of inclination angles is not available on all days; however, this is true for any landing site.)

An interesting situation occurs at an equatorial site for departures from the Moon when the Moon is at the node in its orbit around the Earth. At this time, the reentry points for all trajectory inclinations except 0° occur about 1125 miles from the landing point. This is slightly less than the minimum assumed range requirement of 1200 miles. As a practical matter, nevertheless, landings throughout the entire month should be considered permissible at an equatorial site.

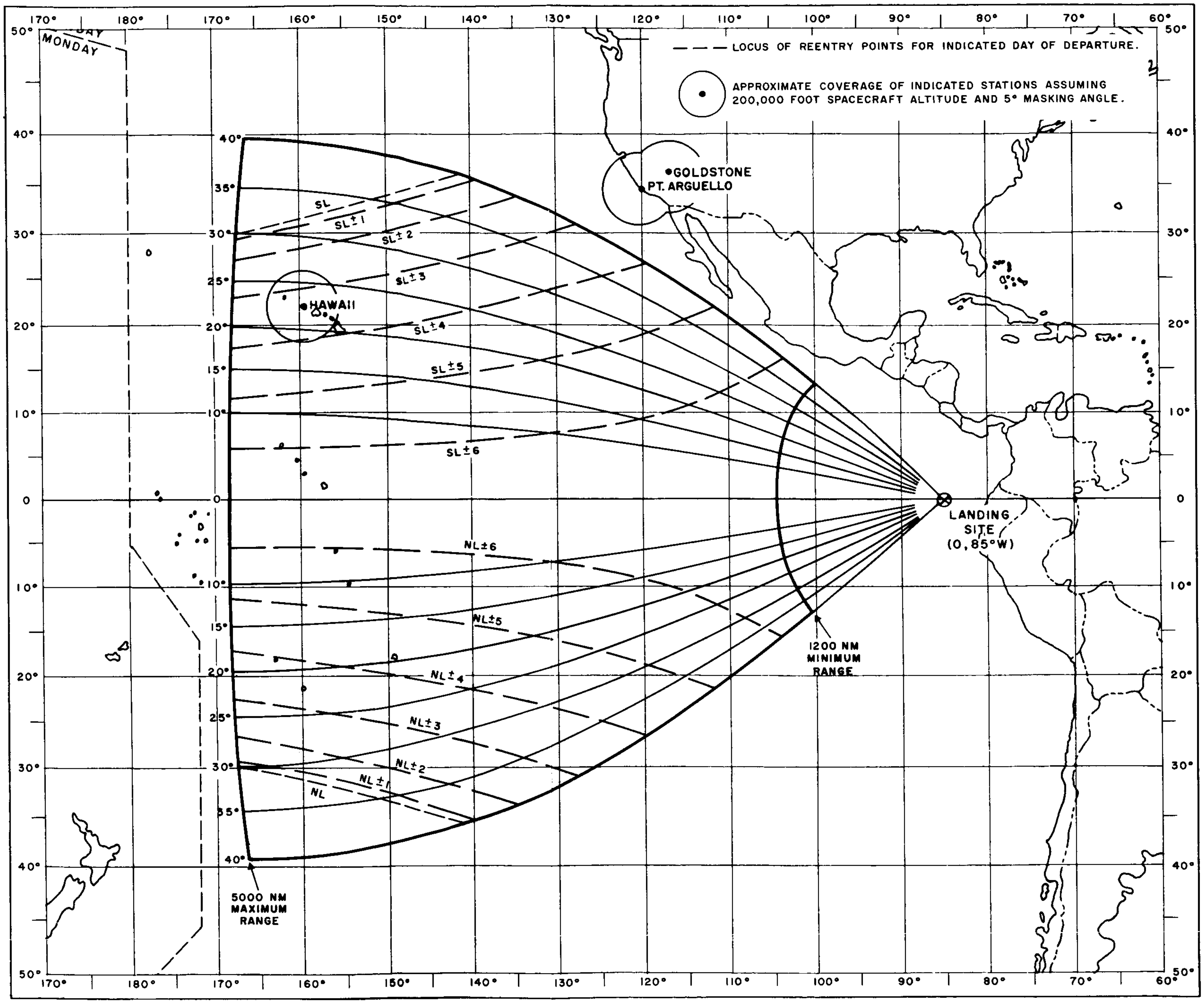

Figure 4-1. Reentry Tracks for Equatorial Landing

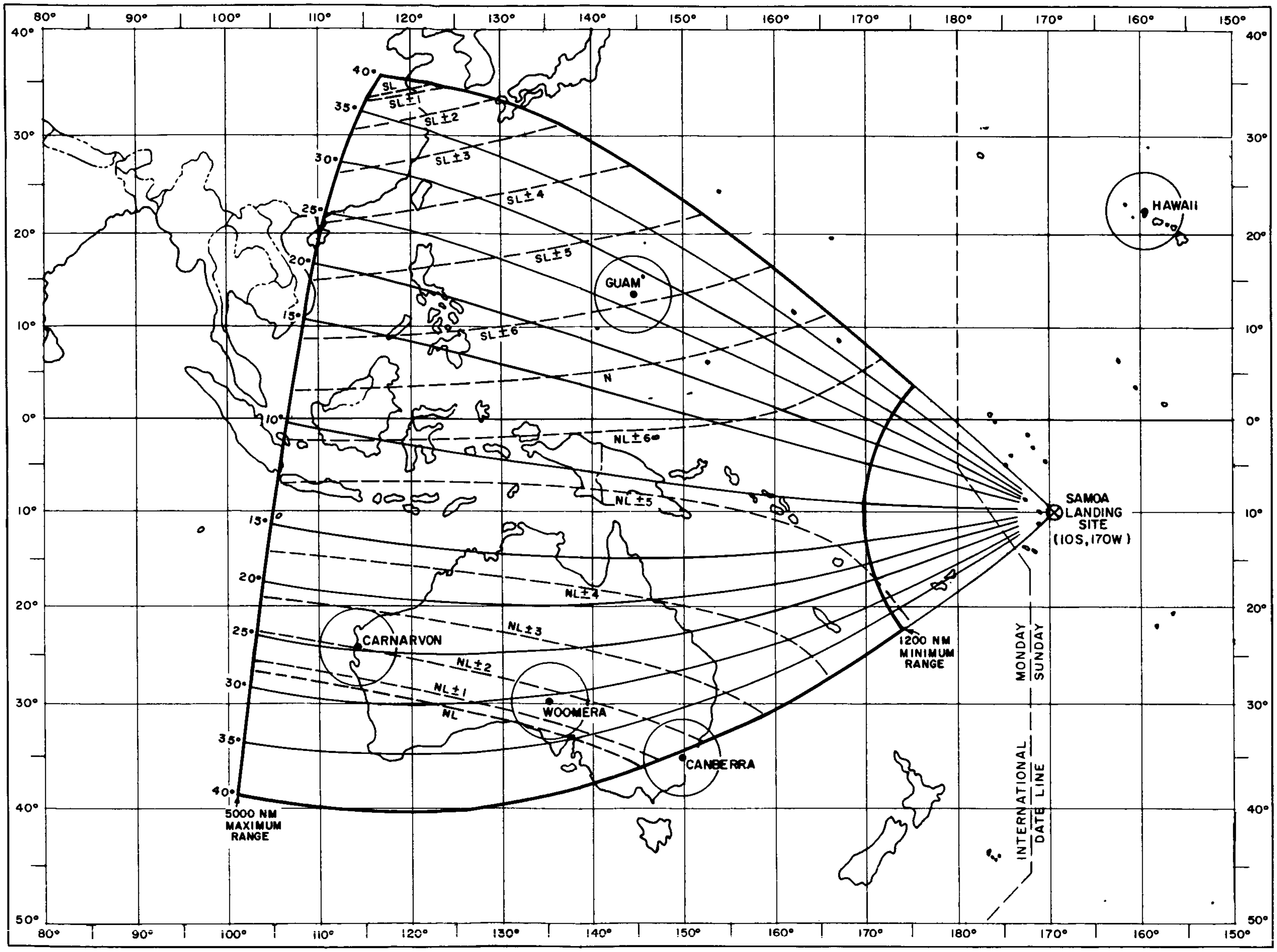

Figure 4-2. Reentry Tracks for Samoa Landing

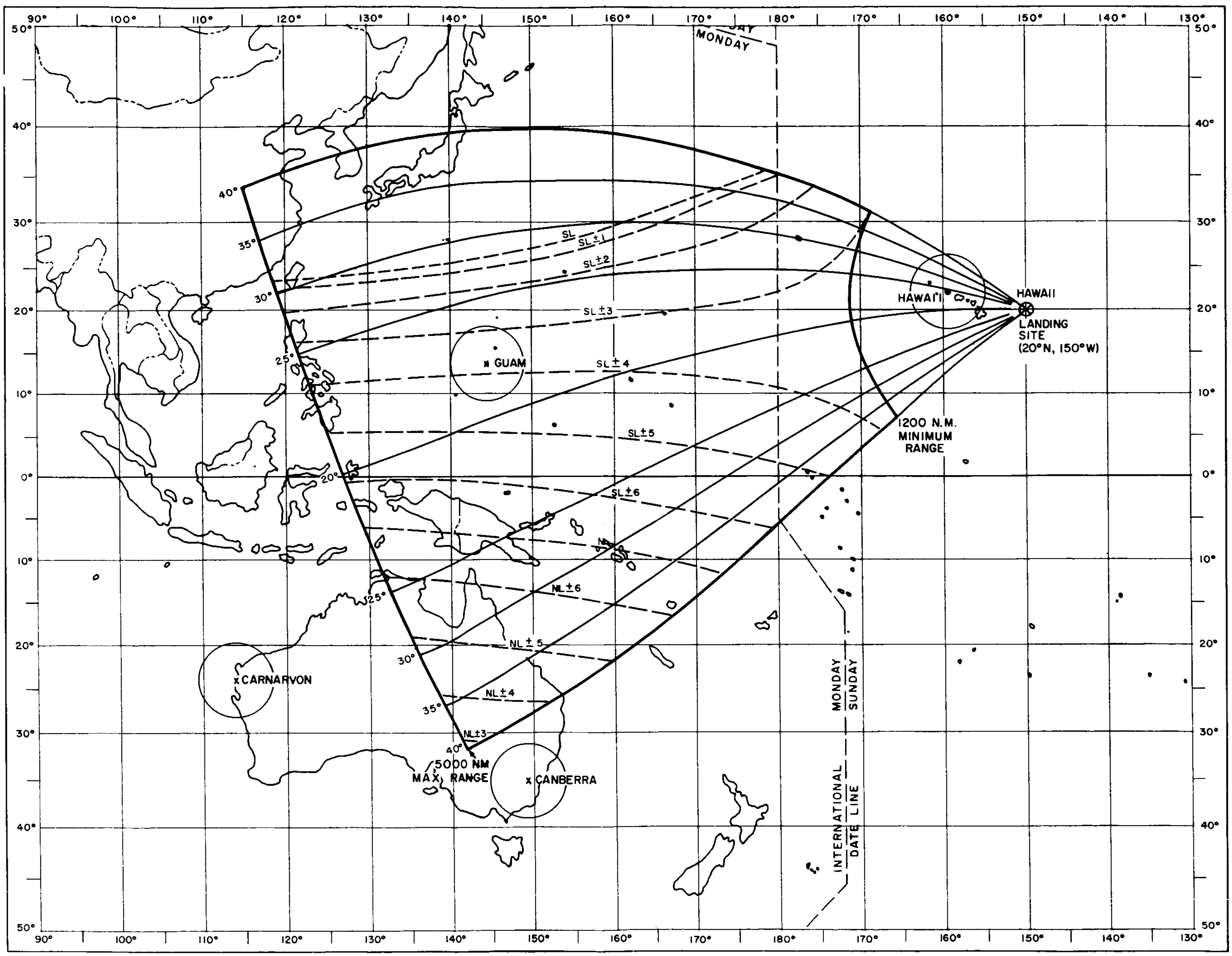

Figure 4-3. Reentry Tracks for Hawaii Landing

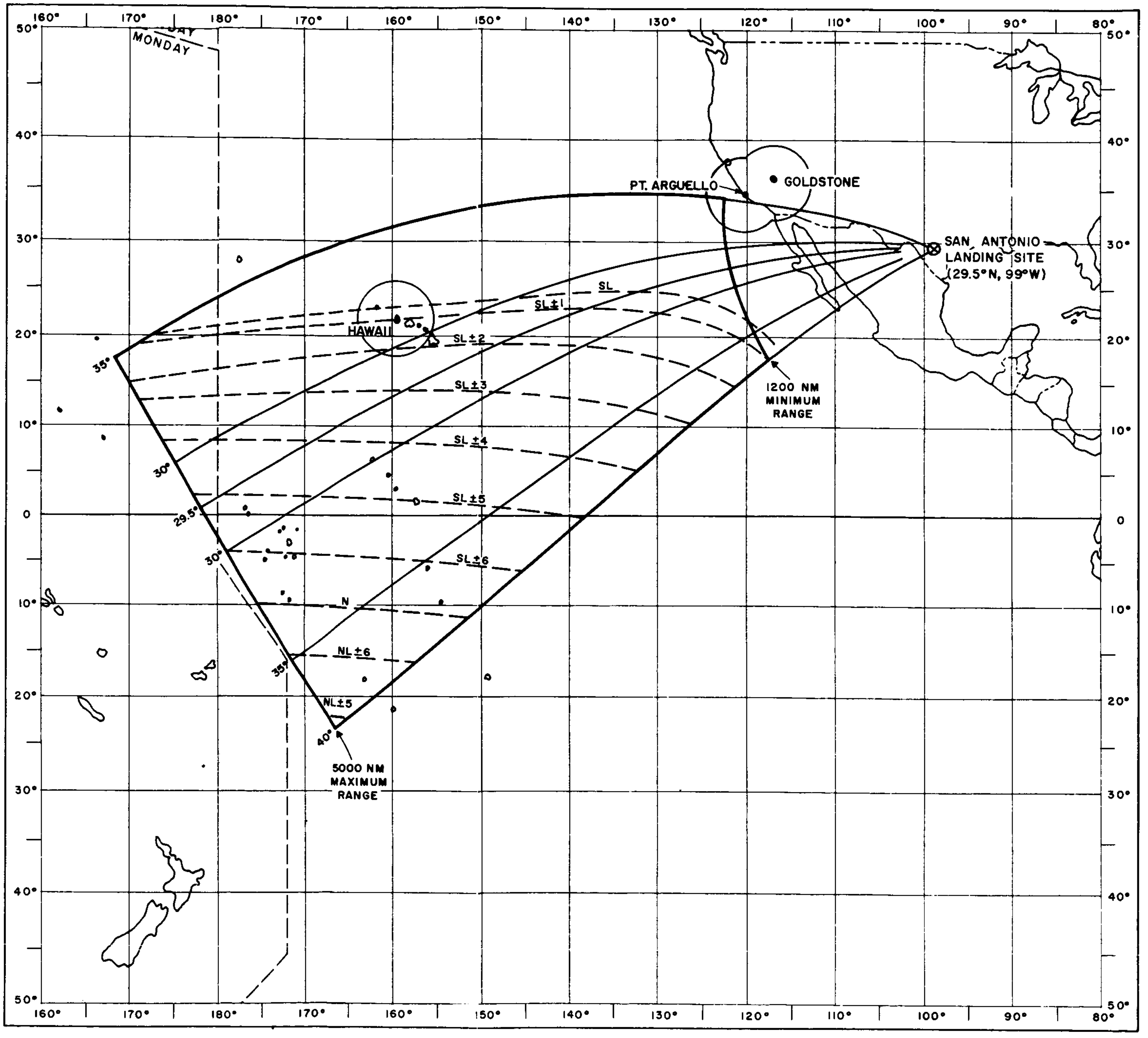

Figure 4-4. Reentry Tracks for San Antonio Landing

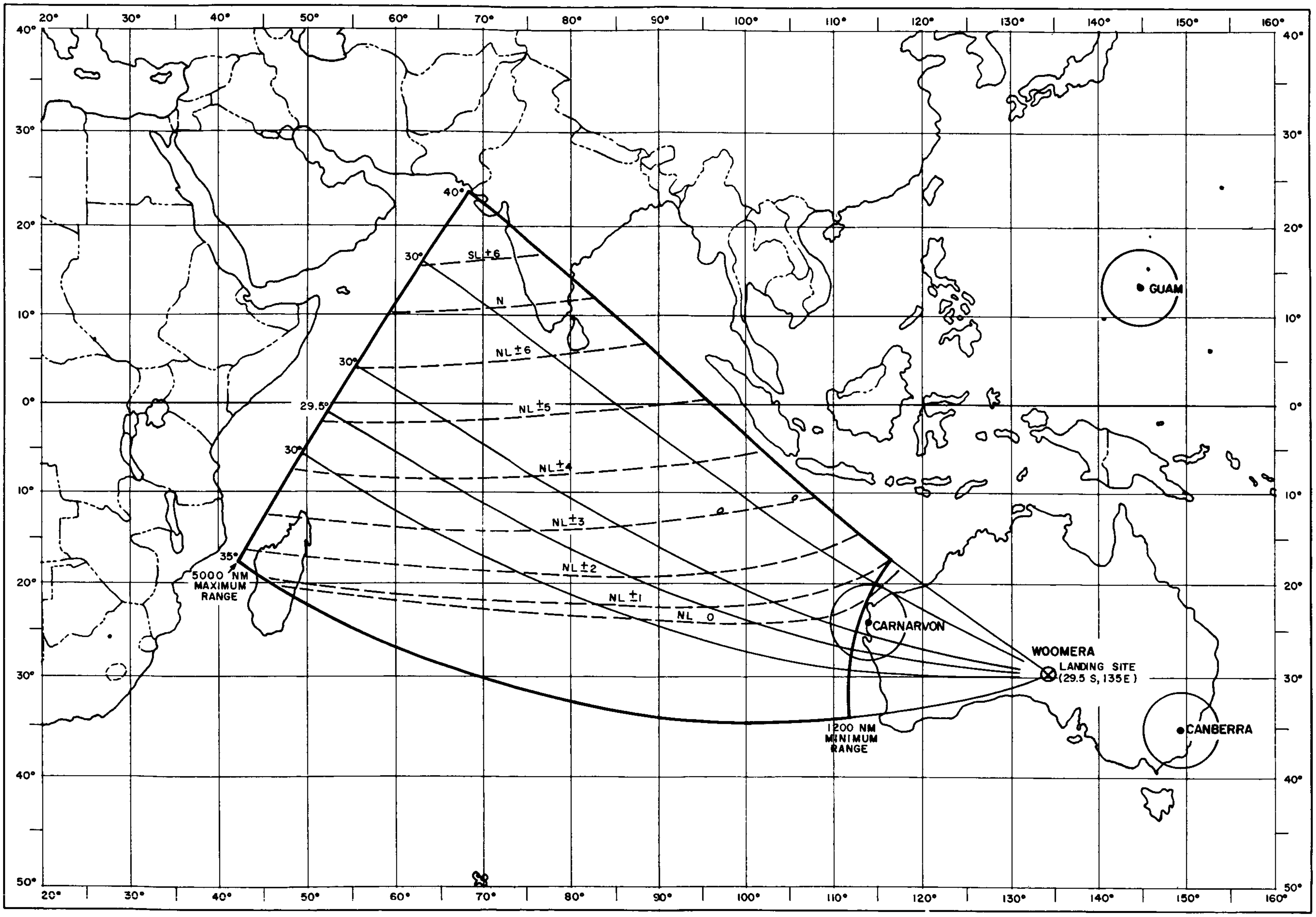

Figure 4-5. Reentry Tracks for Woomera Landing

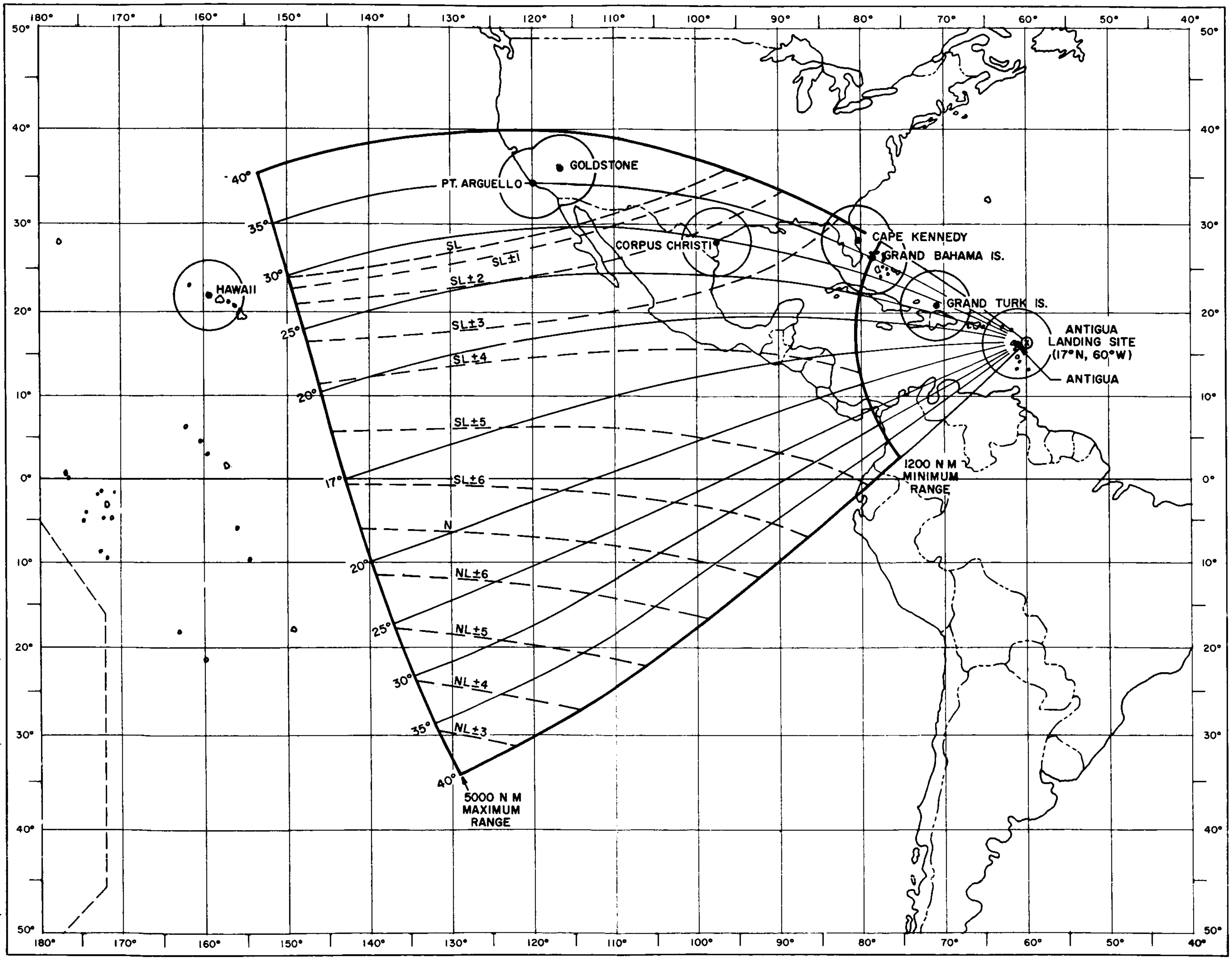

Figure 4-6. Reentry Tracks for Antigua Landing

As landings are considered that are progressively farther from the equator, the number of allowable landing days decreases, as does the spread of allowable inclination angles on many of the remaining allowable days. In the cases of landing sites at 10° latitude (Figure 4-2), all days can still be accommodated, but inclination angles less than 10° are no longer permissible on any day, and the spread of inclination angles on days near one of the lunstices (SL for southern latitude landings, NL for northern latitude landings) decreases significantly. The decreased flexibility is more pronounced for the 20° latitude site (Figure 4-3), several days near NL being eliminated entirely. When the landing site is moved as far as 29.5° from the equator (Figures 4-4 and 4-5), one site can accommodate little more than half of a month.

By pairing up two landing sites, one at a southern latitude and the other at a northern latitude, and making the proper choice between the two at the time of a mission, the restriction on mission flexibility in terms of allowable days of the month can be removed. Some restriction on inclination angles still remains, the extent of the restriction increasing with distance of the sites from the equator.

Reentry Altitude Profiles

In order to discuss ground station coverage during reentry with meaning, it is necessary to take into account the altitude and velocity of the spacecraft as a function of time and position over the Earth. The CM is being designed to be maneuverable after it enters the Earth's atmosphere, and the specific maneuvers undertaken will be dependent on the flight path angle at reentry and on the total reentry range to be flown. Thus, the altitude and velocity profiles that may be traced during a given reentry flight cannot be precisely specified in advance of the mission. Plans for C&T coverage must anticipate the potential spread of profiles considered feasible within the limits of spacecraft design parameters: heating, "g" forces, guidance implementation, etc.

As presently understood, a nominal reentry flight under automatic control of the CM's guidance system may follow either a "ballistic-lob" or a "constant-altitude" profile after the initial descent to an altitude near 200,000 feet. In addition, it is understood that there will be an emergency back-up mode involving a curtailed-range flight profile; flights in this mode would be controlled manually by the astronauts.

Plots believed typical of the ballistic lob category of profiles are shown in Figures 4-7 through 4-11. They are reproduced from Reference 1. Altitude profiles are shown for reentry ranges of 5000, 4000, 3000, 2000, and 1000* nm and

*1200 nm has been assumed in this report as a minimum range. The shapes of the reentry trajectories for 1000 and 1200 nm range are undoubtedly quite similar.

for initial reentry flight path angles of -5.4°, -6.4°, and -7.4°. Velocity profiles are plotted only for a nominal initial reentry flight path angle of -6.4° since velocity profiles for all trajectories of a given length have essentially the same shape. Time-to-go ticks spaced at two-minute intervals are shown for all profiles.

For the -7.4° trajectories, the minimum altitude "trough" of the initial descent is reached about 400 miles beyond the reentry point. The trough is relatively narrow, and the ballistic lob is steep with a high peak altitude. For smaller values of the flight path angle, minimum altitude reached in the initial descent increases and trough position moves farther down range. The trough widens and the ballistic lob becomes shallower, reaching a lower peak altitude. The final descent portion of all trajectories is very similar. For reentry ranges less than about 2000 miles, there would be no ballistic lob.

For the initial descent and ballistic lob portions of all trajectories, the velocity at a given range from the reentry point varies with reentry flight path angle as follows:

$$V(-7.4°) \leq V(-6.4°) \leq V\ (-5.4°)$$

Thus, as flight path angle becomes less steep, the point where orbital velocity is reached moves down range. This down-range shift is about 200 to 300 miles for a change in initial reentry flight path angle of about 1°. The term "orbital velocity" is used here in an approximate sense. The actual velocity during the major portion of the ballistic lob drops slightly below an orbital value, varying from about 25,000 to 23,500 fps over the set of reentry trajectories.

Quantitative information about the nominal constant-altitude mode and the emergency back-up mode was not available for this study. However, it is understood that the initial descent into the atmosphere for either mode would probably be closely identical to the initial descent portions of the ballistic lob trajectories. In the constant-altitude mode, the profile would level out not far beyond the point where the trough occurs in the ballistic lob mode, and the spacecraft would fly at that altitude until it approached the final descent region. It would maneuver laterally as it proceeded down range.

In the emergency back-up mode, the astronauts would guide the spacecraft to a landing in as short a period of time as possible while keeping g-forces within specified limits.

OBJECTIVES FOR REENTRY COVERAGE

The objectives of C&T stations during the reentry phase have been stated in Section 1, Introduction. They are:

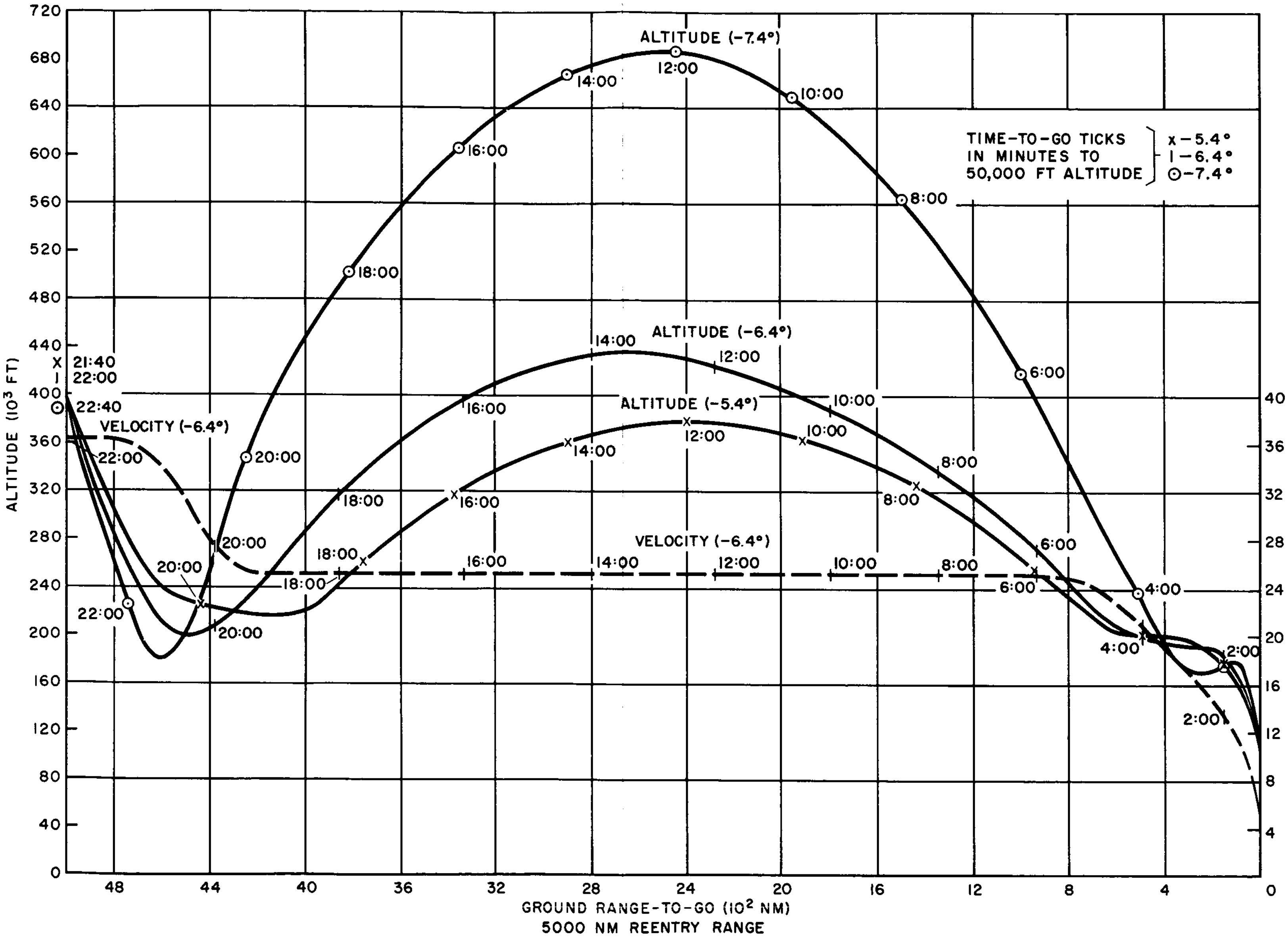

Figure 4-7. Altitude and Velocity Profiles for 5000-Mile Reentry Range

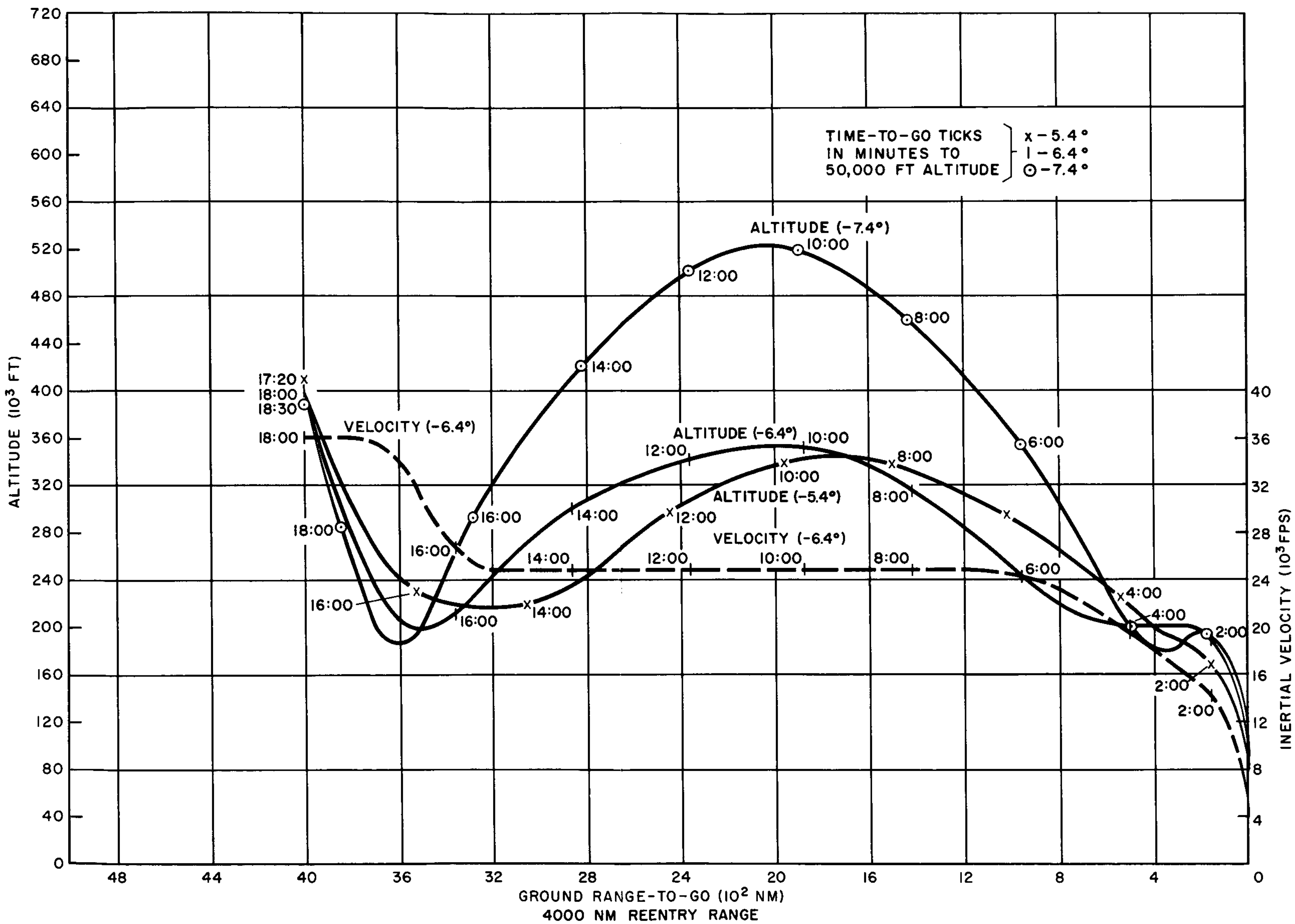

Figure 4-8. Altitude and Velocity Profiles for 4000-Mile Reentry Range

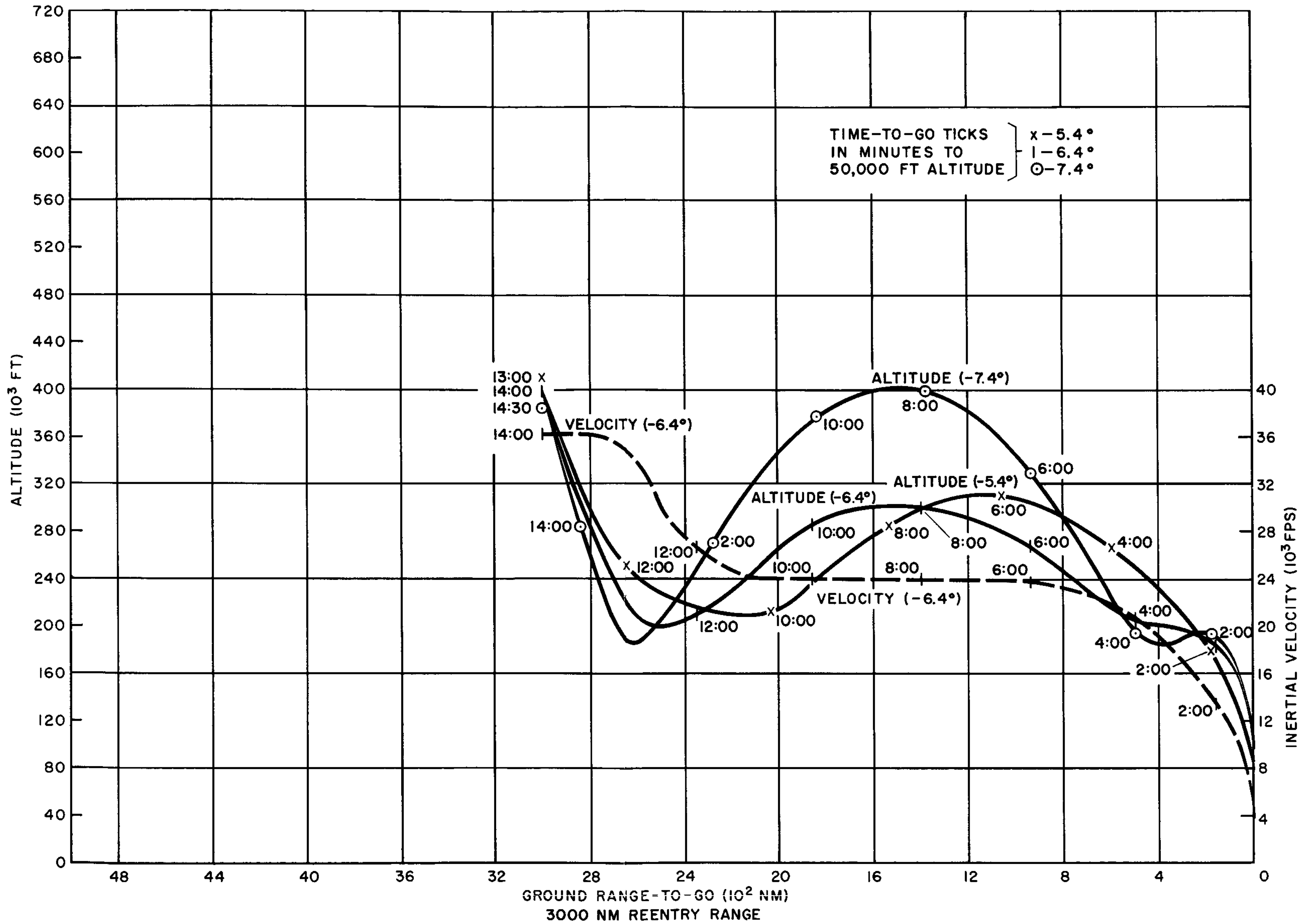

Figure 4-9. Altitude and Velocity Profiles for 3000-Mile Reentry Range

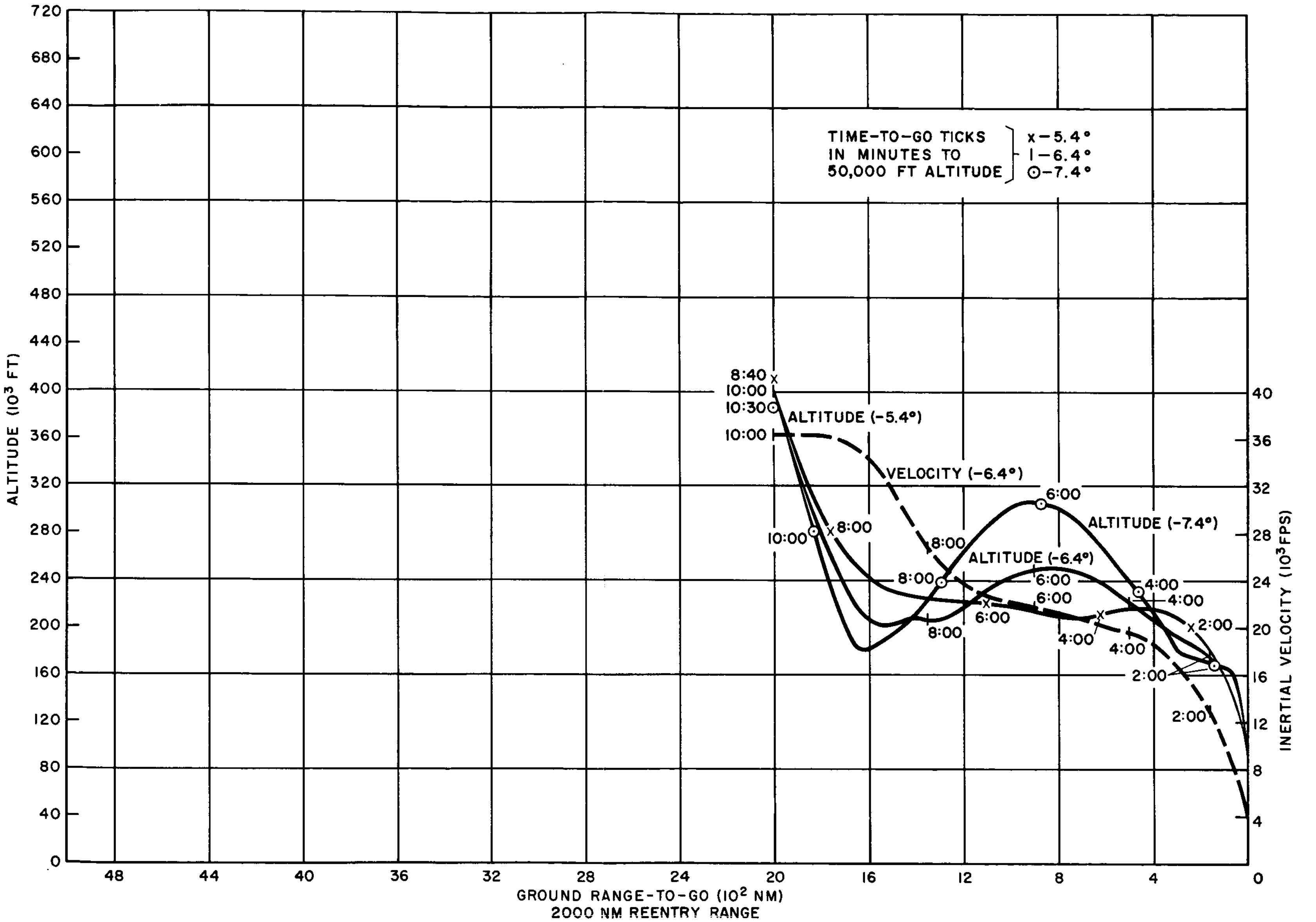

Figure 4-10. Altitude and Velocity Profiles for 2000-Mile Reentry Range

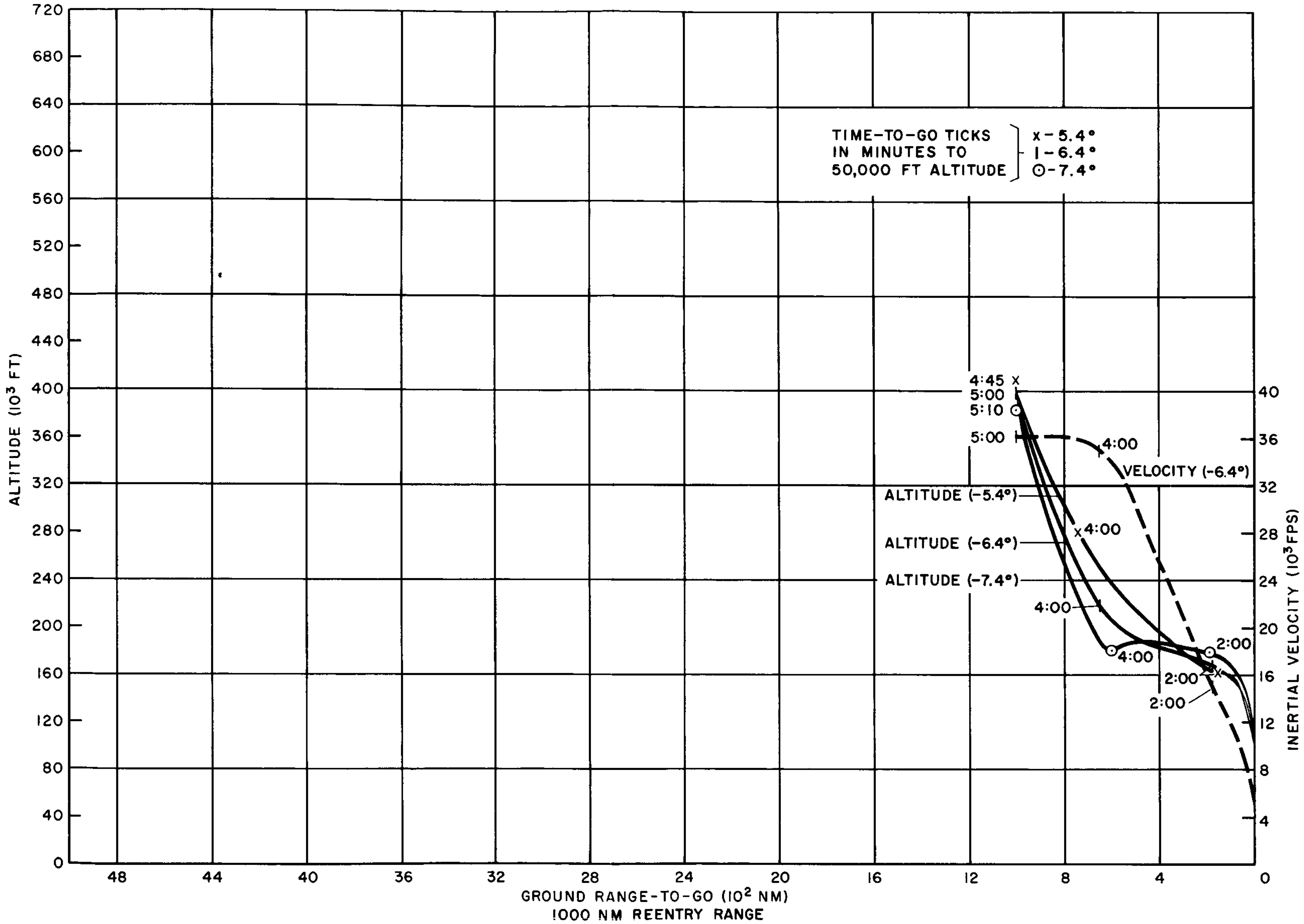

Figure 4-11. Altitude and Velocity Profiles for 1000-Mile Reentry Range

1. To collect sufficient information about the trajectory of the CM to be able to make an estimate of the landing point which will permit expeditious recovery

2. To provide communication with the CM.

These objectives are deliberately stated in very general terms because of the variability of the reentry trajectories as discussed in the previous paragraphs, and because of an uncertainty in knowing the extent of tracking and communications that is essential. If the reentry trajectory is flown precisely as planned, the landing point should be known with sufficient accuracy to permit rapid recovery without any tracking or communication with the spacecraft during the reentry phase. In case the reentry flight does not proceed as planned, an estimate of the new landing point based on tracking data may aid rapid recovery. The extent of the coverage available and of the maneuvering capability available to the CM after the tracking interval affect the accuracy of the estimate. The fact that there is some finite probability of the reentry flight not proceeding as planned has made the first approach — no tracking or communication with the spacecraft at any time during reentry — unacceptable to most people concerned with the problem. On the other hand, the economics of an approach aimed at providing continuous coverage from reentry to landing appears prohibitive, at least for the longer reentry path lengths that are possible.

A compromise between the two extremes that seems reasonable at this stage is to provide coverage to do the following:

1. Give an indication of whether the trajectory being flown is one of the two "nominal" modes — ballistic lob or constant altitude — or is the emergency back-up mode.

2. If the trajectory is one of the nominal modes, verify that either it is or is not progressing approximately as expected, and estimate the landing point.

3. If the emergency mode is detected, track the spacecraft during enough of its descent to establish a good prediction of its landing point.

4. Communicate with the spacecraft to the extent permitted by reentry plasma effects and by the visibility limits of the stations providing the tracking coverage to accomplish 1 through 3.

What constitutes a "good" prediction in item 3 is open to debate. Examination of the final descent portions of the altitude profiles for a 1000-mile reentry in Figure 4-11 suggests that, if tracking could be done until the spacecraft reaches 150,000-feet altitude, the landing point should be predictable within a few miles. These profiles apply specifically to nominal trajectories. However, it seems reasonable that the profile of an emergency mode reentry would not differ drastically from that of a 1000-mile nominal reentry trajectory, since the latter is understood to be near the minimum range considered allowable within g-force limits, and the emergency mode is also considered to be planned for minimum range with g-force limits.

The discussion of reentry flight profiles in the section entitled, Reentry Altitude Profiles, has brought out two points that are particularly significant in deciding where C&T stations ought to be located along the reentry trajectories to accomplish the general and specific objectives stated above. The first point is that there is expected to be negligible lateral maneuver between the 400,000-foot reentry point and the trough of the initial descent. Thus, the coordinates of the trajectory prior to the trough region should be quite accurately predictable from knowledge of the reentry point coordinates and the reentry flight path angle (both of which are presumed to be accurately known from pre-reentry tracking data). The second point made was that the selection among the three flight modes — nominal ballistic lob, nominal constant altitude, or emergency mode — should become apparent shortly after the trough is reached. These considerations lead to the conclusion that it is important to be able to start tracking the spacecraft near the bottom of the trough. The fact that there is no definable trough for some of the shorter-range reentries does not alter the desirability of tracking after the initial descent segment, since the choice between the nominal constant-altitude and the emergency mode presumably is still available in these cases.

A station that is located properly downrange from the trough to begin tracking when the spacecraft reaches the trough will be in a position to observe about 500 miles of trajectory (more, if a ballistic lob trajectory is flown). This should be adequate to determine whether a nominal or emergency trajectory has been chosen, and whether or not it appears to be progressing normally. If the emergency mode is adopted after the initial descent, the station will also be in a position to track the spacecraft through a substantial part of its remaining flight.

Whether or not communication with the spacecraft during the visibility interval will be possible using the station location concept just described will depend largely upon plasma effects. Quantitative estimates which have been made of plasma phenomena appropriate to an Apollo-type reentry have not yet had experimental verification (References 6, 7, and 8). However, there is reason to believe that all communication signal frequencies thus far planned for the CM will be blacked out during the initial reentry descent and for some time after the trough is reached. In the case of the constant-altitude and emergency flight modes, the blackout may persist through most or all of the visibility region of a station located as suggested. Thus, under the present concepts of reentry trajectories, it seems that the assumption must be made that communication with the spacecraft may or may not be available, and operational system planning should proceed accordingly.

The following discussion of coverage for specific reentry trajectories is concerned only with station locations selected to observe the region immediately after the initial reentry descent to about 200,000 feet. There is no clear basis at this time for requiring that further coverage be provided along the trajectory path, except near the final stages of the spacecraft's descent to the landing point. It will be assumed here that adequate coverage in this region is provided by recovery forces.

COVERAGE OF REENTRY TRACKS

In contrast with the pre-reentry tracks discussed in Section 3, the method of deriving reentry tracks does not include means for calculating related altitude and time data. These parameters are given in the series of reentry altitude profiles described above. However, the great variability in these profiles makes it impractical to include altitude and time information analytically in the reentry ground track computations. As a consequence, it is also impractical to calculate visibility limits for specific ground stations along each trajectory. To fill this gap in a limited way, a somewhat pessimistic approach was used here which assumes that the minimum reentry altitude over the major portion of a track governs station visibility. This minimum altitude is taken as 200,000 feet, corresponding to a visibility circle of approximately 260 nm radius at a masking angle of 5°.

Coverage by Land Stations

Coverage circles of 260 nm radius are shown on Figures 4-1 through 4-6 for a number of land C&T station locations. The stations included are those assumed in Section 2.

It is immediately obvious from these illustrations that the reentry coverage offered by the assumed set of land stations could not satisfy the coverage objectives stated earlier unless limits were imposed on Apollo missions in terms of trajectory inclination angles and days when missions are conducted. For all landing sites studied, except possibly Antigua, the limits required would restrict mission flexibility to an intolerable extent. Referring to the Antigua case (see Figure 4-6), it is notable that those trajectories that have inclination angles between about 30° to 40°, and approach Antigua from the northeast, fall within the visibility limits of a number of existing stations. Within these inclination angle limits, return trajectories could be accommodated for about three to four days before and after SL — a total spread of about seven days. This may or may not be a sufficient spread to be interesting from an Apollo mission planning viewpoint; the purpose here is only to point out the fact that significant coverage by land stations is possible for this landing site if certain mission restrictions can be imposed.

The meager coverage generally provided by the land stations assumed for this study, together with the fact that a vast percentage of the reentry trajectories shown on the illustrations pass over water areas, has suggested that consideration be given to the use of ships.

Coverage by Ships

Ship coverage has been analyzed only for the five Pacific Ocean landing sites assumed in this study. However, the general concepts of ship deployment discussed below would apply as well to coverage for landings at Woomera, San Antonio, or Antigua. It is quite conceivable that any ships stationed in the Indian Ocean for the injection phase could be re-deployed to provide reentry coverage for a Woomera landing as well.

In line with objectives stated in Objectives for Reentry Coverage, the principal coverage need is believed to start at the time the initial reentry trough is reached. Since the location of this trough can vary over a wide area as a function of the day of the month and the trajectory inclination angle with respect to the equator, it follows that the optimum location of a ship to start tracking at the reentry trough will also vary. Given a specified day and trajectory inclination, the trough can vary further from about 400 to 900 miles downtrack from the initial reentry point, depending upon the reentry flight path angle. (See the altitude profiles, Figure 4-7.) A 500-mile figure (corresponding to the nominal reentry flight path angle of -6.4° used in generating the ground tracks) is used in this reentry analysis. The effect of deviations from this nominal value is discussed in the next section. Since the minimum altitude of the spacecraft at the bottom of the trough is about 200,000 feet, the radius of coverage of the ship will be about 260 miles, the same as that of the land stations assumed earlier. Thus, the ship should be located no more than 260 miles downrange from the bottom of the trough or 760 miles from the reentry point.

Figure 4-12 shows again the set of reentry ground tracks for the equatorial landing site. Also shown in a series of dashed lines, called "ship locus lines" hereafter, along which ships should be positioned for coverage of trajectories terminating at this site. Each of these dashed lines corresponds to a specific day of the month, and each intersection of a ground track with one of these lines is 760 miles downrange from the reentry point for that same track. The 4500-mile boundary at the left indicates the farthest position of the reentry trough from the landing site, corresponding to a 5000-mile reentry range and the nominal -6.4° reentry flight path angle. The 4240-mile boundary indicates the farthest distance of the ship from the landing point required in order to begin tracking when the spacecraft reaches the trough of the longest range trajectories.

1. <u>Coverage Required for Nominal Day Only</u>. The extent of coverage along any ship locus line that can be provided by one ship depends on how long before reentry the ship is informed of the position it is to occupy, how fast it can move, and whether or not coverage must be planned for more than the nominal day of landing. Let it be assumed initially that coverage must be planned to accommodate only a nominal landing date, which presumably will be known on the day that a mission starts. (The requirements for covering a spread of landing times will be considered later.) The appropriate locus line along which a ship should be positioned initially will then also be known on the day of launch. The nominal reentry point coordinates will be determined no later than the time of trans-Earth injection. Thus, the desired position for the ship along the locus line will be determined at that time as well. By the fourth assumption on page 1-3 in Section 1, this will be known at least 60 hours prior to reentry, and so the ship will have that much time, or more, to move from its initial position to the final desired position along the locus line indicated at the time of trans-Earth injection.

A major assumption that must still be made is the speed at which the ship can move. This will be taken as 10 knots, recognizing that higher speeds probably will be possible, but that some margin is desirable to allow for less than ideal steaming conditions and for somewhat greater distances that might have to be covered for reentry cases other than the nominal variety considered here. Assuming, then, that 10 knots can be maintained over the spacecraft's 60-hour minimum return flight time, the ship can move as much as 600 miles in any direction from its initial position on the ship locus line. Thus, one ship is restricted to 1200 miles of locus length in order to be in a position to track the spacecraft during an overhead pass. Some additional allowance might be made for trajectories passing to either side of the ship; however, the visibility times for passes directly overhead will be only of the order of two to three minutes, and the further reduction that would be entailed by a pass off to one side does not seem advisable. A further reason for limiting the planned ship coverage to overhead passes is to provide some margin for cross-range maneuvering by the spacecraft, which would also tend to reduce the length of the trajectory falling within a ship's visibility circle.

Given the capability to cover a total spread of 1200 miles along one of the ship locus lines in Figure 4-12, the important remaining question is which 1200-mile segment of the locus should a ship be assigned to cover. It appears that a reasonable objective to adopt for this analysis is to cover the greatest possible spread of trajectory inclinations on any given day. (Ultimately, as constraints on mission dates, lunar parking orbit inclination and orientation, fuel budget, etc., are fully understood, it may be possible to limit the required coverage to specified portions of the ship loci.)

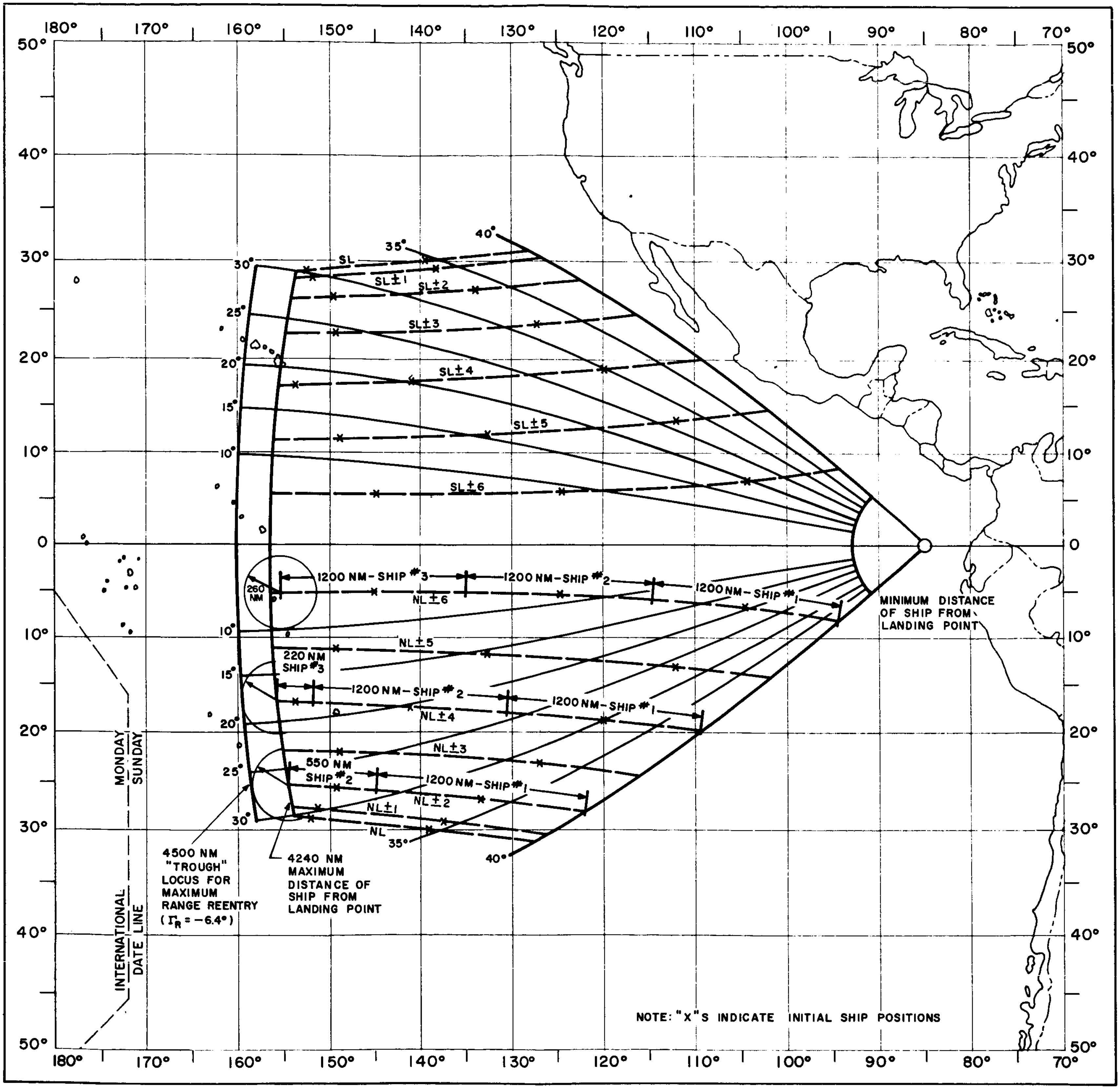

Figure 4-12. Ship Coverage for Equatorial Landing Site Planned for Nominal Landing Day Only

From the various reentry maps presented thus far, it is clear that the greatest spread of inclination angles is always found toward the eastern boundaries of the tracks for a given day, that is, the region of highest inclination angles. Thus, if only one ship were available, it should be located initially on the ship locus line for a specified day at a point 600 miles from the easternmost end of that line. It will then be able to travel as much as 600 miles in either direction along the locus line to reach a trajectory specified at the time of departure from the Moon. If the specified trajectory crosses the ship locus line farther west than 600 miles from the initial ship position, that ship will not be able to provide coverage (unless, of course, the flight time is greater than 60 hours or the ship can move faster than 10 knots).

If a second ship is available, it should initially be located no more than 600 miles west of the westernmost coverage provided by the first ship; a third ship should be similarly located no more than 600 miles west of the westernmost coverage of the second ship, etc.

Figure 4-12 illustrates the above strategy. The X's along each dashed line indicate the desired initial positions for ships. The limits of the coverage provided by ships #1, #2, and #3 for the following three illustrative days are also indicated:

1. On NL ± 6, ships #1, #2, and #3 each cover 1200 miles along the locus line. The third ship does not quite reach out to the maximum limit of the reentry trough boundary, but for all practical purposes the gap is negligible. Although each ship covers 1200 miles along the ship locus line, there are wide differences in the spread of inclination angles covered by each. Ship #1 covers the spread from 12° to 40°, ship #2 from 7.5° to 12°, and ship #3 from 6° to 7.5°.
2. On NL ± 4, ship #1 covers 24° to 40°, ship #2 covers 18° to 24°, and ship #3 adds coverage only from about 17.5° to 18°.
3. On NL ± 2, ship #1 covers 29° to 40°, ship #2 adds 27° to 29°, and ship #3 is of no value.

Figure 4-13 lists the total spread of inclination angles available each day for an equatorial landing site and the coverage offered by each of three ships deployed as described above. It is apparent that one ship alone can provide a very high percentage of the total possible coverage when the criterion for such coverage is to position ships so that they cover the greatest spread of inclination angles on the nominal landing day. A second ship can cover an additional 10% to 25% of the possible trajectories, depending on the day of the month, while a third ship adds coverage for only a few percent of the trajectories on certain days of the month.

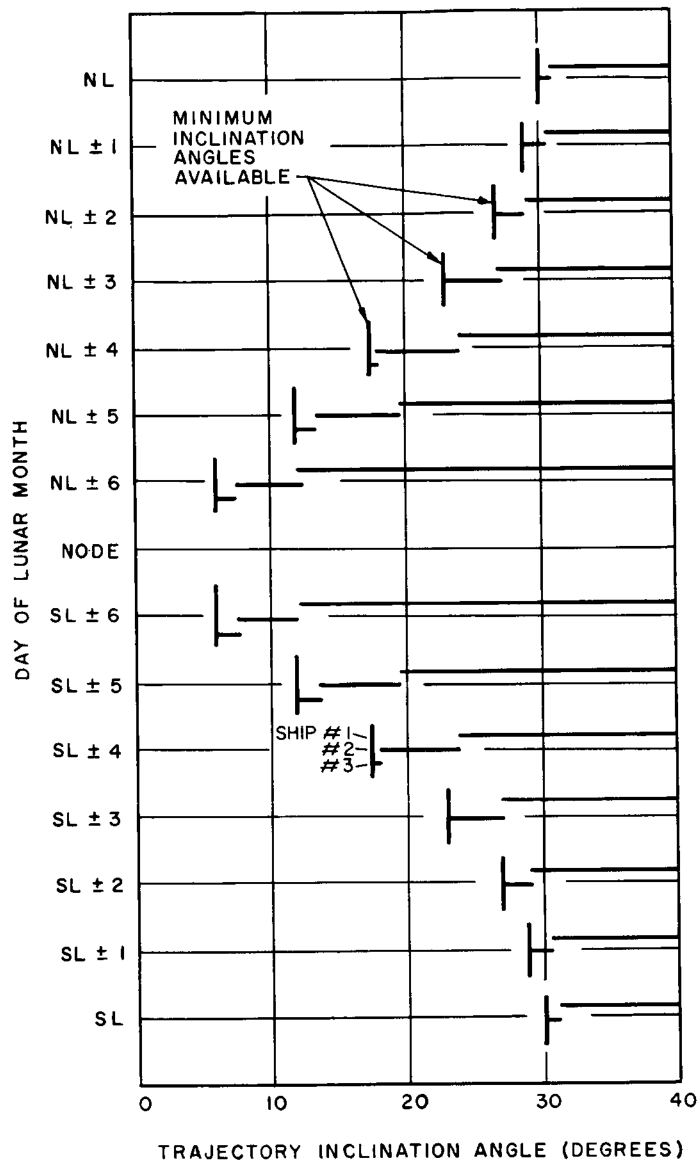

Figure 4-13. Spread of Trajectory Inclinations Covered by Ships on Nominal Landing Days Only — Equatorial Site

Figures 4-14 and 4-15 provide similar data for the -10° latitude site near Samoa and the +20° site near Hawaii. In developing these charts, consideration was given to the fact that the reentry points and required station positions for many of the days near NL fall on land masses, particularly Australia (see Figures 4-2 and 4-3). The regions blocked by such land masses (relatively small islands were ignored) are indicated by dashed-line segments in the bar charts.

A feature noted in Figures 4-2 and 4-3, that does not appear in the equatorial site case, is the trend of the inclination angles on certain days. Refer to NL ± 4 on Figure 4-2, for example. The trajectory inclination for the westernmost reentry point on that day is 17-1/2°. Farther east, along the ship locus line, a minimum trajectory angle of about 17° is reached, after which the angles increase once again. This behavior arises from the fact that, for some inclinations, there are two possible reentry points within the limiting ranges of 1200 to 5000 miles, as discussed in the section entitled, Reentry Ground Tracks. Such cases are noted in the ship coverage illustrations by a bar entry for ship #3 beginning at a higher inclination angle than the minimum for ship #2.

Another feature notable in Figure 4-14, and in all subsequent illustrations involving sites at 10° latitude, is the maximum inclination angle of 25° on days NL ± 5, whereas for other days the maximum is 40°. The explanation is that the reentry ranges for trajectories with inclinations between 25° and 40° are slightly less than 1200 miles (see Figure 4-2), hence inadmissible by one of our assumptions. In all practicality, the difference is so small that it is probably insignificant, but it has nevertheless been recognized for the sake of consistency.

The general conclusions reached with regard to the value of 1, 2, and 3 tracking ships in the equatorial landing case apply as well to the Samoa site at -10° latitude and to the Hawaii site at +20° latitude. That is, one ship alone covers a high percentage of the total possible trajectories, a second ship covers 10% to 25% of the possible trajectories on some days, and a third ship adds coverage for only a few percent of the trajectories on certain days.

2. <u>Coverage For Landings on Nominal Day, One Day Earlier, or One Day Later</u>. The criterion assumed for the ship coverage capabilities analyzed above has been that landings would occur on only one designated day of the month. As a practical matter, some spread of possible landing times probably must be anticipated. At minimum, it may be necessary to require the spacecraft to orbit the Moon for some time after the CM-LEM rendezvous in order to time the return trajectory properly for a landing at a designated point on the Earth. Further contingencies that should be admitted include the possibility of returning from the Moon after a few orbits (without a landing having been made) and the possibility of a lunar exploration phase longer than the one-day period generally taken as nominal.

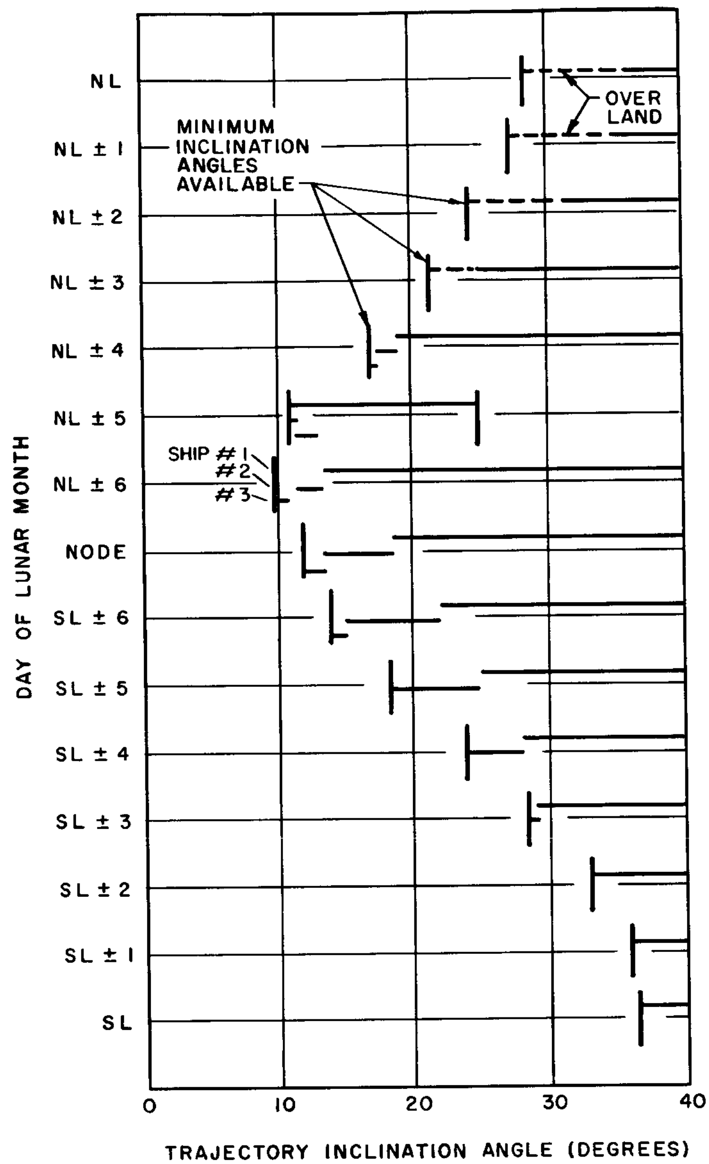

Figure 4-14. Spread of Trajectory Inclinations Covered by Ships on Nominal Landing Days Only — Samoa Site

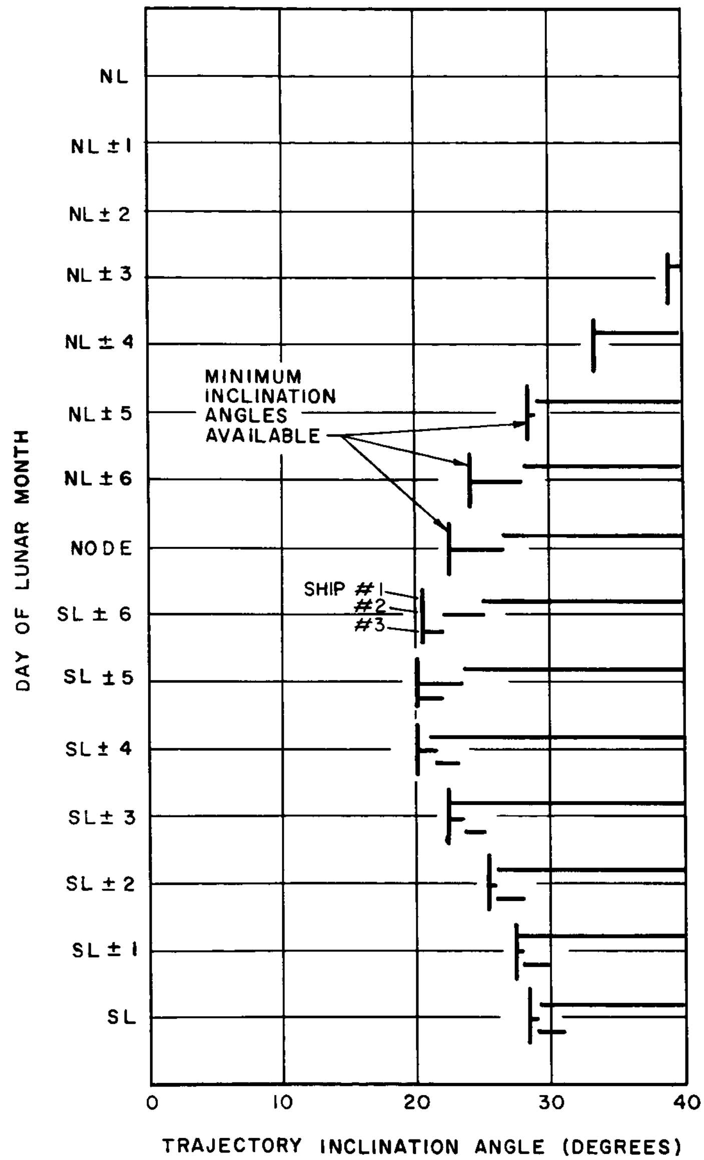

Figure 4-15. Spread of Trajectory Inclinations Covered by Ships on Nominal Landing Days Only — Hawaii Site

Such potential variations in the nominal mission profile indicate that a spread of reentry times of about 24 hours before and after a nominal reentry time is worth considering. Given the objective of accommodating landings for a nominal day, one day earlier, or one day later, the coverage capabilities of ships can be expected to differ from the results presented in the previous paragraphs. The implications of such an objective will be examined here.

Another change of a practical nature will be included in the following analysis. The previous ship coverage data have been generated by considering each landing site separately. In the case of the equatorial site, this is reasonable and the same approach will be followed again for that site. However, the discussion to this point has demonstrated that mission flexibility, in terms of allowable days and/or return trajectory inclinations, suffers increasingly as the landing site is moved to higher latitudes. Thus, it is desirable to consider two sites, one above and the other below the equator, as a pair intended to accommodate landings at different times during a month. On any particular day, the site offering the largest spread of return trajectory inclinations would generally be picked, that is, if the criterion adopted earlier for analyzing ship coverage is reasonably valid.

In addition to a single site on the equator, then, this analysis has considered two pairs of landing sites: (1) the sites near Samoa and Hawaii, illustrated in Figures 4-2 and 4-3; and (2) sites at +10° and -10° latitude, both at 130°W longitude. The choice of latitude for the latter pair was made to illustrate a case somewhat intermediate to that of the equatorial and paired Hawaii-Samoa cases (although the Samoa site has also been assumed at -10° latitude). The longitude of 130° was selected to have the reentry trajectories avoid large land masses, and thus allow unrestricted ship movement for C&T coverage purposes.

Assumptions with regard to tracking objectives, desired ship locations to cover a given reentry trajectory, ship speed, etc., are the same here as they were for the previous analysis of coverage for separate sites and nominal landing days. One additional objective will be adopted, however; coverage provided by the ships (whether 1, 2, or 3 ships are involved) should leave no gap in the spread of inclination angles between the maximum (40°) and the minimum that can be covered by the ships on each of the three days. The basis for this objective is an assumption that the flexibility offered by a wide spread of trajectory inclination angles is just as important for landings on a day before or after a nominal date as on the nominal date itself.

Figure 4-16 indicates the desired ship deployment for the equatorial site. The ground tracks, ship position loci, maximum range boundary, etc., are the same as in Figure 4-12. The two-part arrows along each dashed line indicate ship positions and direction of movement to cover landings on three successive days of possible spacecraft departure from the Moon. The middle of the arrow in each case

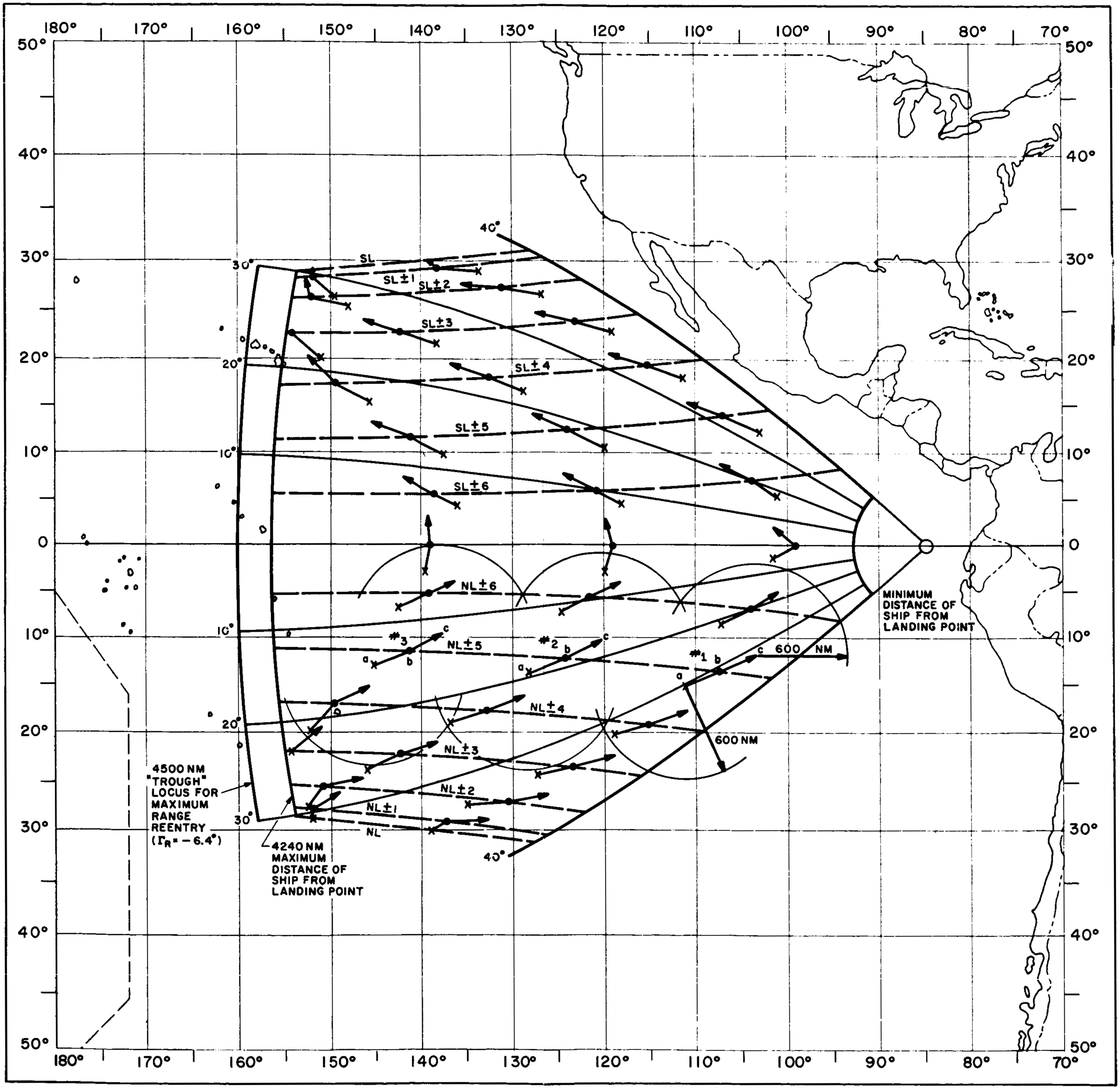

Figure 4-16. Ship Coverage for Equatorial Landing Site, Planned for Nominal and ± One Days

falls on the ship position locus line for the nominal day in the three-day spread. The ship should be at that position if the spacecraft leaves the Moon at the nominal time. The X at the foot of each arrow represents the position that the ship should occupy initally to provide coverage for departures one day earlier, while the head of the arrow indicates the position it should occupy if departure occurs one day later than the nominal day.

To illustrate the deployment strategy in more detail, refer to the indicated positions and movement of ship #1 for a nominal departure at NL + 5. Initially, on NL + 4, this ship should be at position a. If the spacecraft leaves the Moon on that day (i.e., one day earlier than planned), the ship can travel at least 600 miles during the return flight time and reach any point along the NL + 4 locus within the 600-mile arc drawn about position a. Note that the coverage provided by ship #1 is relatively inefficient for that day; this is part of the penalty paid for requiring coverage of more than the nominal day.

As soon as it becomes known that the spacecraft will not leave the Moon at the earliest opportunity on NL + 4, ship #1 should begin steaming toward position b on the NL + 5 locus line. The distance between a and b is 240 miles, which can be traversed in 24 hours at a speed of 10 knots. If the spacecraft leaves the Moon at the nominal time on NL + 5, the ship can then steam along the locus for that day in either direction to cover trajectory inclinations as far west as 600 miles or as far east as the limiting 40° trajectory. The distance from point b to the 40° trajectory inclination is less than 600 miles on most of the nominal days, another compromise imposed by the requirement to cover a three-day spread of landing times.

If the spacecraft does not depart from the Moon on the nominal day, the ship should begin steaming toward the position c at the head of the arrow. Again, this is 240 miles from position b and can be reached in 24 hours. From this point, the ship can steam an additional 600 miles during the trans-Earth flight time to reach any point along the NL + 6 ship locus line within the 600-mile arc drawn around point c. Note that this arc just reaches the intersection between the NL + 6 locus and the 40° trajectory. This is the point which largely governs the entire positioning of ship #1 as described. Similarly, the westernmost intersection of the 600-mile arc around position c and the NL + 6 locus governs the position of ship #2, and the intersection of the similar arc around position c for ship #2 governs the positioning of ship #3. As the ships move northward to the SL days, the requirement of covering the day prior to the nominal day of departure becomes the controlling feature of the strategy.

After the SL day is reached, the indicated movement of the ships is exactly reversed. The head of each arrow on the illustration now becomes the tail and indicates the desired position of the ship one day earlier than the nominal day of departure. Similarly, the foot of the arrow becomes the head and represents the desired ship position one day later than a nominal departure date.

The resultant spread of trajectory inclination angles covered by each of three ships has been compiled in Figure 4-17. Only the data for the NL half of the month are presented for this site, since the data for the SL half are symmetrical. (Only the results for the northward movement of the ship complex are given in the chart to avoid making the illustration too complex to read.) As implied in the previous paragraph, the results for any given "nominal" day after SL for southward movement of the ships would be identical to the results for the same nominal day before SL in the northward progression. The results for one day earlier than the nominal date in the southward progression would be identical to those for one day later than nominal in the northward progression, and vice versa.

It may be worth noting that the coverage provided by ship #1 does not depend on the availability of ships #2 and #3. Similarly, if the #1 and #2 ships are available, their capabilities are as indicated, independent of whether or not the third ship is provided.

Figure 4-18 illustrates the coverage for the pair of sites at ±10° latitude. It can be observed on Figure 4-18 that the ship locus lines for the two landing sites on the "Node" day cover identical spreads of longitude and are separated by only a few degrees of latitude. Thus, it becomes a natural point of transition to consider landings at the -10° site on days from NL to the Node, and at the +10° site on days from the Node to SL. The two-part arrows again indicate positions and movement of ships throughout the month, and the resultant coverage is indicated in Figure 4-19.

Figures 4-20 and 4-21 present the same type of information for the Samoa and Hawaii sites considered as a pair. In this case, the transition from one landing site to the other was made between the NL ± 6 days for Samoa landings and the Node for an Hawaii landing. A slightly greater spread of inclination angles could be covered on some days by making the transfer between the Node day of the Samoa set and the SL ± 6 days of the Hawaii set. However, the ship deployment strategy becomes more complicated when this is done.

Examination of Figures 4-17, 4-19, and 4-21 indicates that the relative values of 1, 2, and 3 ships are about the same as they were in the case of coverage for nominal days only. One ship alone can cover a high percentage of the permissible trajectory inclinations on each day. If the overlapping coverages of the first and second ships are ignored, the coverage provided by the second ship beyond that of the first is a maximum of about 7-1/2° (out of a total available spread of 29-1/2°), occurring on the Node day for the pair of ± 10° latitude sites. On most day, the additional spread of inclination angles covered by ship #2 is on the order of 2 to 5°.

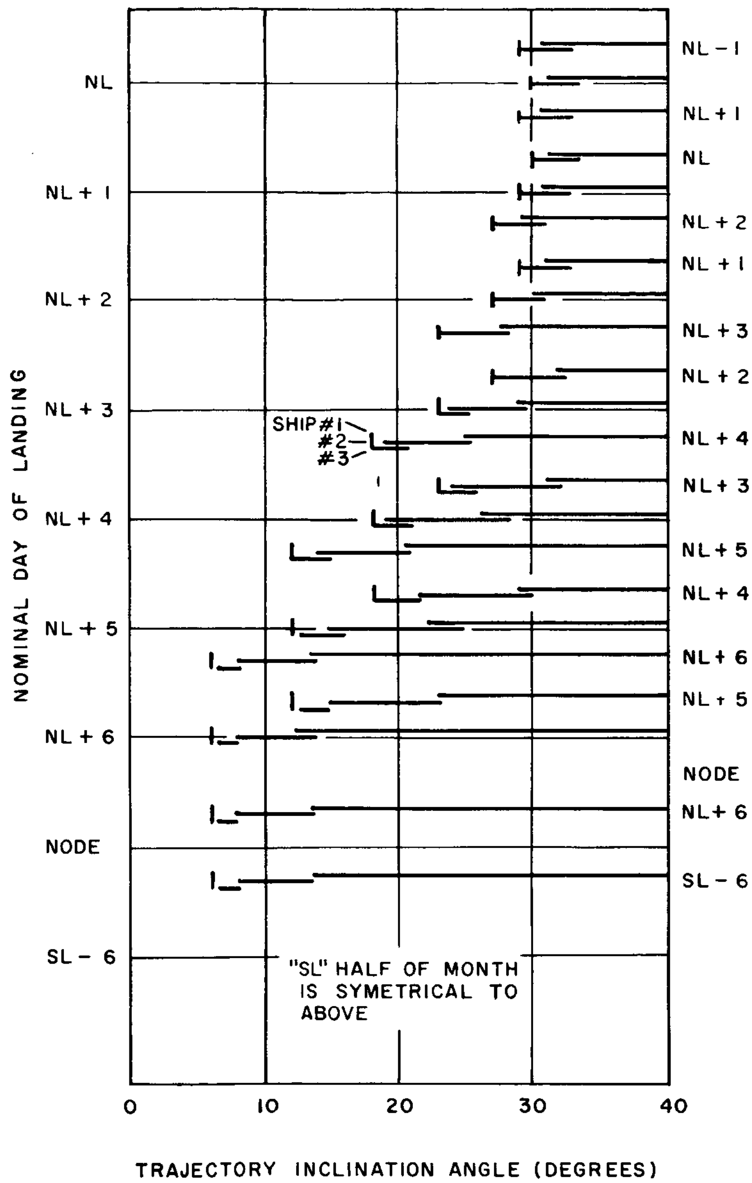

Figure 4-17. Spread of Trajectory Inclinations Covered by Ships for a 3-Day Spread of Landing Dates — Equatorial Site

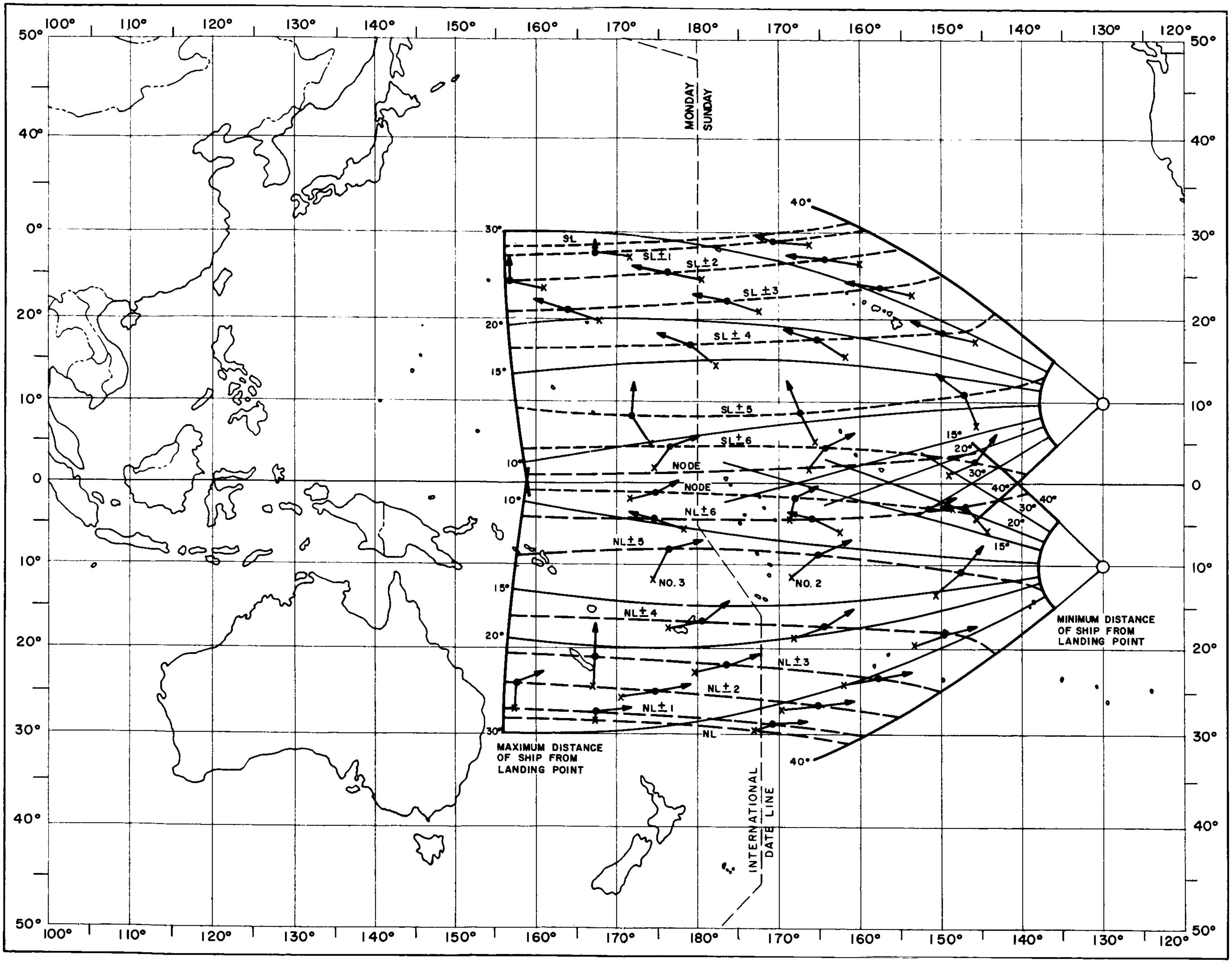

Figure 4-18. Ship Coverage for Paired Landing Sites at ± 10° Latitude, Planned for Nominal and ± One Days

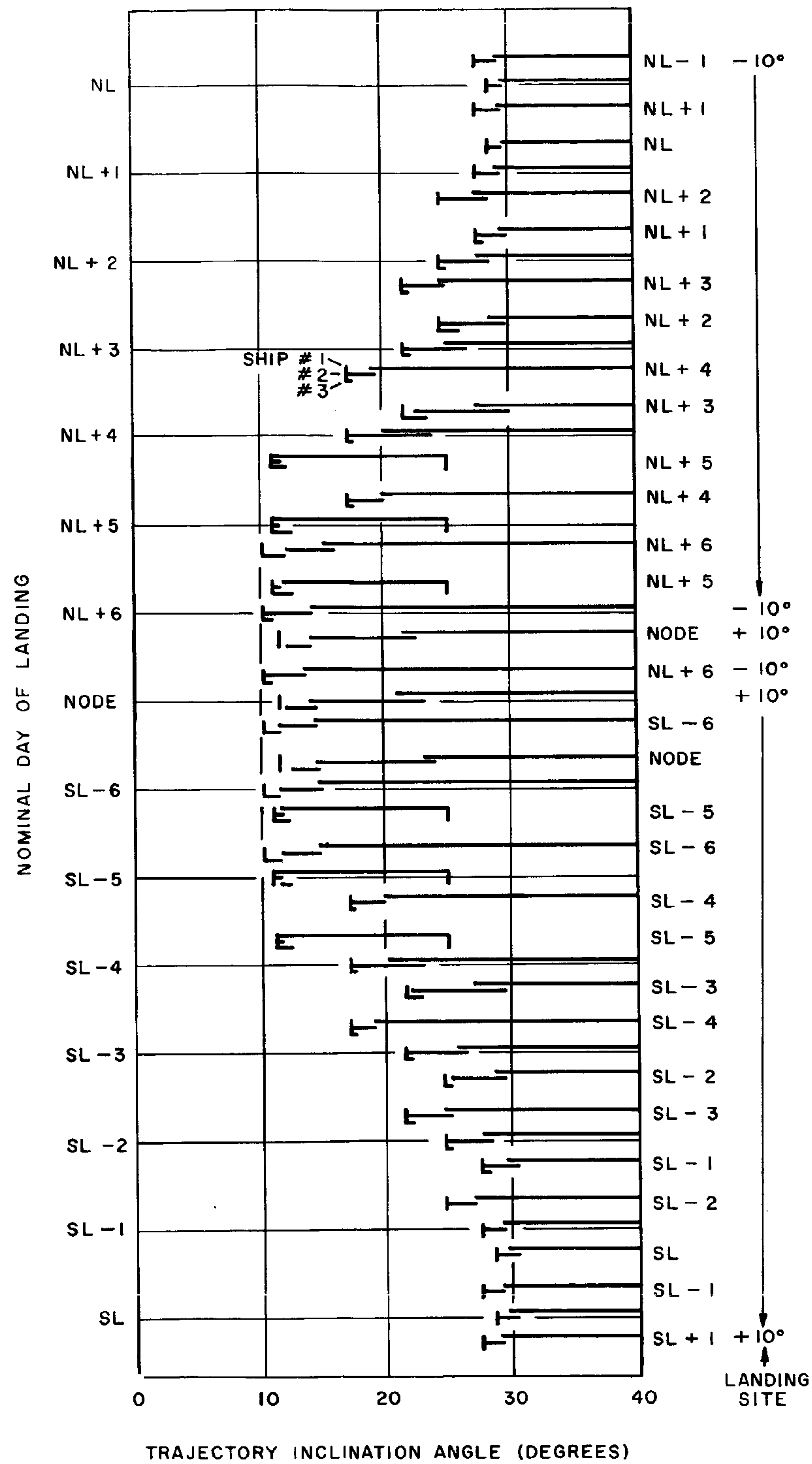

Figure 4-19. Spread of Trajectory Inclinations Covered by Ships for a 3-Day Spread of Landing Dates — Paired ± 10° Latitude Sites

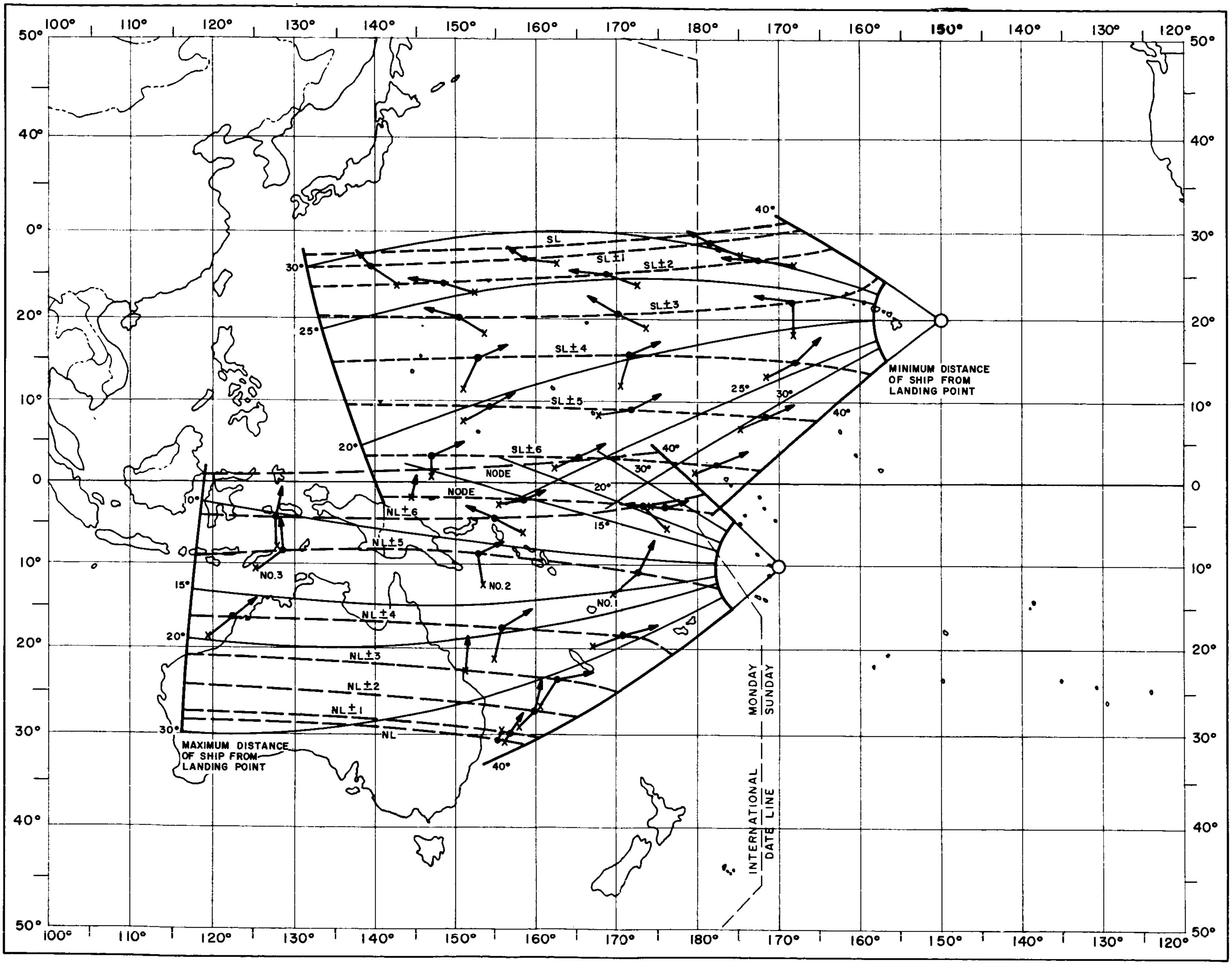

Figure 4-20. Ship Coverage for Paired Hawaii-Samoa Sites, Planned for Nominal and ± One Days

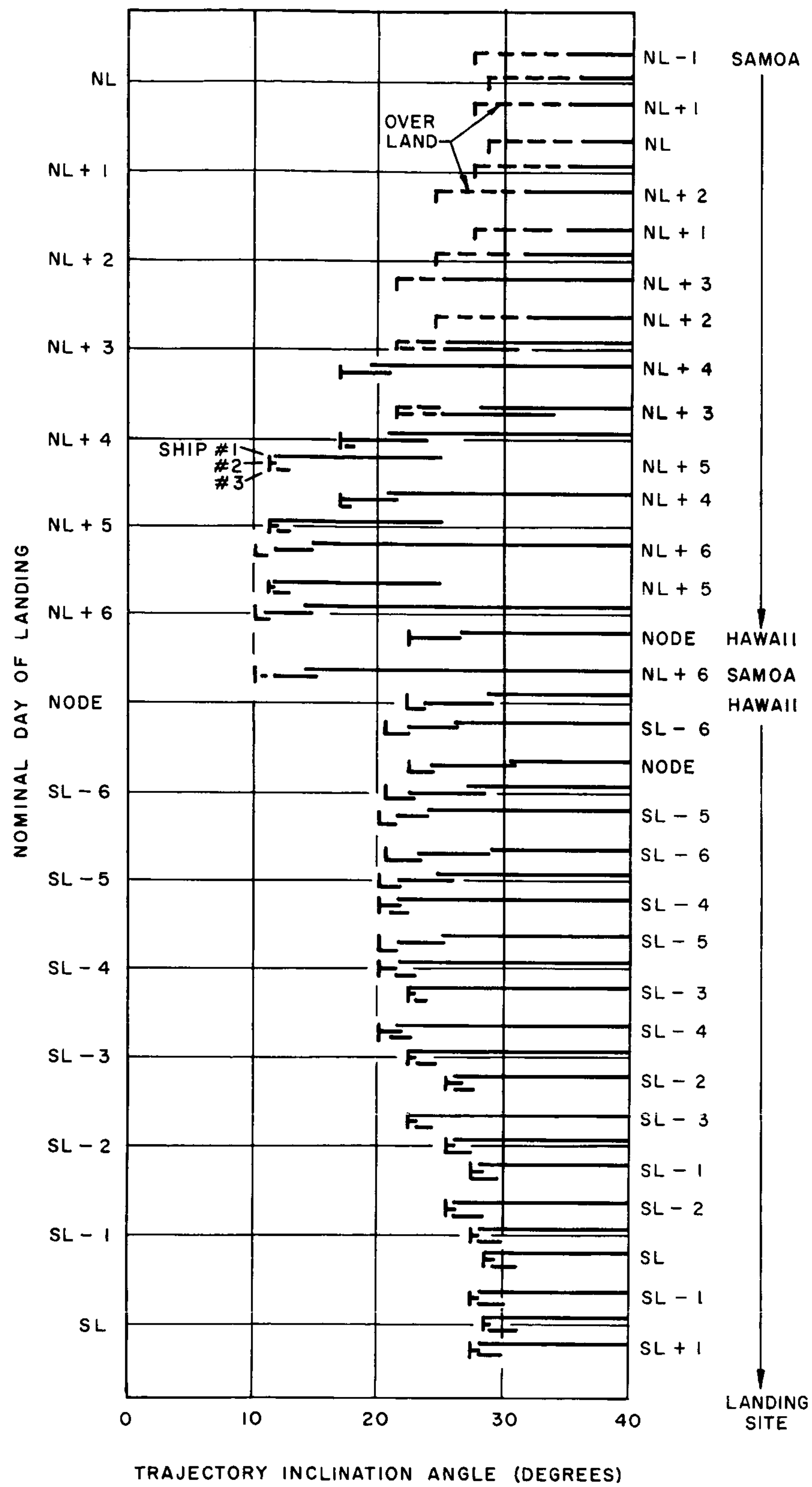

Figure 4-21. Spread of Trajectory Inclinations Covered by Ships for a 3-Day Spread of Landing Dates — Paired Samoa — Hawaii Sites

Ship #3, as before, adds coverage for only a few degrees of trajectory inclination even though it covers substantial distances along the ship locus lines.

Apart from the coverage capabilities provided by each ship on a specified day, a question arises as to the ability of a ship to move from its designated initial position for one nominal day of landing to its designated initial position for another nominal day of landing. Such movement would be required in the event of launch delays from day to day. Reference to Figures 4-16, 4-18, and 4-20 indicates that the greatest separation between ship positions specified from one day to the next occurs for days near the Node of the Moon's orbit, and toward the easternmost region of the reentry tracks. The greatest separation encountered is approximately 600 miles. Let it be assumed that a reentry tracking ship is at its specified initial position on the day planned for an Apollo launch. This will be nominally about seven days before a return landing is expected. Next, suppose that the launch is held one day. The ship now has at least four days — the one-day launch delay, plus three days for the trans-Lunar flight — to travel to the position it should be occupying when the spacecraft has its first opportunity to leave the Moon. (If the mission proceeds nominally after the delayed launch, there will be the additional time of the lunar orbit and landing available for further ship movement.) During these four days, the ship's speed of 10 knots allows it to travel as much as 960 miles, so that it can easily accomplish the necessary move.

If the launch were held for several days in succession, the required ship movement could be more than permitted by a speed of 10 knots, unless some of the delay is "anticipated" in the initial positioning of the ship. Thus, the ship location on the first possible day of launch might be chosen as much as three days travel time ahead of the position it should occupy for the initially-planned nominal day of spacecraft departure from the Moon. Then, if the launch is <u>not</u> delayed, the ship can move to its designated position within the 72-hour trans-lunar flight time.

An analysis of the required ship movement from day to day to compensate for launch holds has been made, taking into account the time available for such movement, the distances between desired ship positions on successive days, and assuming the ship adopts a "leading" strategy as described above. The analysis indicates that launch delays at least as long as six days could be accommodated. Such a spread of launch opportunities for any one mission is probably greater than would be allowed by other considerations.

Effects on C&T Coverage of Variations in Nominal Parameters

The entire ship coverage analysis for the reentry phase has thus far been based on assumptions of "nominal" values for certain parameters. It is pertinent to consider now some of the effects on ship coverage capabilities of variations from nominal values for the following:

1. Trans-Earth time of flight
2. Reentry flight path angle
3. Antenna masking angle

The minimum trans-Earth flight time has been taken as 60 hours, and all ship deployment strategy has been based on this value. By assumption 4 on page 1-3, the flight time might be as long as 110 hours. Any variation in flight time affects the coordinates of the reentry point. If two different flight times are considered (for the same reentry flight path angle), the trajectory for the longer time will sweep over a slightly greater angle with respect to a line between the Earth and the Moon than will the shorter time of flight. Both the additional time of flight and the change in sweep angle would have to be taken into account in timing the departure from the Moon to permit landing at a designated site on the Earth. However, from the standpoint of reentry coverage, the reentry point must still fall within 1200 to 5000 miles from the landing point. Therefore, the qualitative effect of a longer flight time alone on ship coverage for reentry tracking is to allow more time for ship movement than was allowed in the foregoing analysis.

A change in flight time may or may not be accompanied by a change in reentry flight path angle. For a fixed time of flight, a change in reentry flight path angle will be accompanied by a change in trajectory sweep angle, and hence also a change in the location of the reentry point. The change in reentry point is rather small — on the order of 2°, or 120 nm — as the reentry angle is varied from the nominal value of -6.4° to either extreme of -5.4° or -7.4°. Relative to a set of reentry trajectories for a -6.4° reentry angle, such as those illustrated in Figures 4-1 through 4-6, the general effect of a steeper reentry (-7.4°) is to cause the reentry points to fall about 120 miles farther from the landing point. (If a -6.4° reentry point is already at the 5000-mile maximum range limit, then the reentry point for a steeper angle would be outside that limit and would represent an inadmissible condition by the assumption previously stated.) Along with the movement of the reentry point farther from the landing point, the distance between the reentry point and the trough of the reentry trajectory also narrows by about 100 miles (see Figure 4-7). Thus, the position of a ship that is to begin tracking the spacecraft when it reaches the trough of a -7.4° reentry trajectory should generally be about 220 miles farther from the landing point than for a -6.4° reentry. The approximate net effect on the ship deployment strategy, if it is required that a spread in reentry flight path angle from -6.4° to -7.4° be accommodated, would be to decrease slightly the spread of trajectory inclination angles that can be covered by each ship.

The effect of shallower reentry angles is more pronounced. Again, for a fixed time of flight, the change in the reentry point itself in varying the reentry angle from -6.4° to -5.4° is about 120 miles (in this case toward the landing site). In addition, the distance between the reentry point and the rather poorly-defined trough for a -5.4° reentry trajectory is about 900 miles, or about 400 miles more than that of the -6.4° reentry case (see Figure 4-7 again). If a ship were stationed 260 miles from this trough toward the landing site, as assumed in the ship coverage analysis, the indicated position would be 1160 miles from the reentry point, and about 520 miles closer to the landing point than its indicated position for a -6.4° reentry. This may seem like a severe handicap in ship deployment and it might mean that the criteria for ship location and movement would have to be modified for shallower reentry angles. However, the specific effect on initial ship positioning and ship movement strategy will not be apparent until the quantitative relationships between — and constraints on — time of flight, reentry flight path angle, etc., are better understood.

It is worth noting one factor that tends to make the specific results of this ship coverage analysis, in terms of numbers of ships required and the coverage provided by each, insensitive to the possible variations in trajectory parameters just discussed. In stating assumption 4, page 1-3, concerning trans-Earth time of flight, it was indicated that the minimum value of 60 hours used in this work is likely to be increased as Apollo mission plans materialize. Any such increase would allow more time for ship movement to compensate for the spreading of reentry points, resulting from variations in trajectory parameters.

With regard to antenna masking angle, it is perhaps enough to cite the experiences of Project Mercury as a basis for assuming that 5° masking is a reasonable criterion for defining visibility limits for tracking purposes, but is overly conservative for communication purposes. Thus, plasma effects permitting, communication should be possible at ranges greater than the 260-mile limit adopted for the tracking coverage analysis. If communication is assumed possible for all visibility angles above the local horizon at a land or ship station, the range capability would be about 480 miles with the spacecraft at 200,000 feet.

Effect on C&T Coverage of Variation in Landing Point Location

For reasons of mission flexibility, it may be desirable to select Apollo landing points from a relatively large geographical area located near the nominal landing point, e.g., Hawaii or Samoa. The effect on the strategy of ship deployment when continuous variation in landing point location is allowed has not been examined. However, certain observations can be made.

If the landing point is varied only in longitude, the desired positions for a reentry tracking ship shift by the same amount and in the same direction that the landing point is shifted. The size and shape of the region requiring coverage remain unchanged. This is evident from the fact that the sets of reentry tracks to all sites at the same latitude are identical; hence the relative positioning of a ship with respect to a reentry point or to the landing point is the same for all such sets of tracks.

Changes in the latitude of the landing site affect both the locations of the individual ship positions relative to each other and the overall shape of the region requiring reentry coverage for the particular landing site. Figure 4-22 illustrates the effect on individual ship positions and contours for landings at 20°N, 10°N, and on the equator, all at the same longitude. Four nominal landing days are chosen for illustration. The contours represent loci of desired ship positions on those days. (These loci are redrawn from previous illustrations employed in the ship coverage analysis.) Various trajectory inclinations are noted along the contours. Desired positions for ships to cover those trajectories if the same objectives are adopted as in the earlier ship coverage analysis are shown by X's.

Comparison of the indicated ship positions along the curves for a selected day of the month and for the three different landing site latitudes gives an idea of the amount of ship movement that would be necessary to accommodate the change in latitude. To a first approximation, the amount of ship movement appears to be about the same as the shift in the landing point; i.e., a shift in latitude of 10°, or 600 nautical miles, calls for a change in tracking ship location of that magnitude but probably in a different direction. Whether or not such a change in position presents a great problem depends on when the change of landing sites is made. If it is made at the time of launch, ships could move the required amount during the translunar flight. If the choice is delayed until departure from the moon, the required ship movement, added to that previously indicated to place a ship at the right point along a locus line, may exceed the capability of the ship.

If changes in landing point are made during the course of mission planning, the effect on the shape of the overall region requiring reentry coverage must be considered. Figures 4-16, 4-18, and 4-20 illustrate the overall characteristics of the regions containing the loci of required ship positions for landing sites at latitudes of 0°, 10°S, and 20°N. The ability of ships to provide coverage in each of these regions has been demonstrated. Since the ship coverage capabilities for these individual areas were found to be generally similar, the same general results should apply for landing sites with latitudes anywhere in the range of 0° to 20°, and very probably to higher latitudes as well.

The results of this study should, therefore, be applicable when, in the course of mission planning, landing sites with specific latitudes different from those discussed in this report are considered.

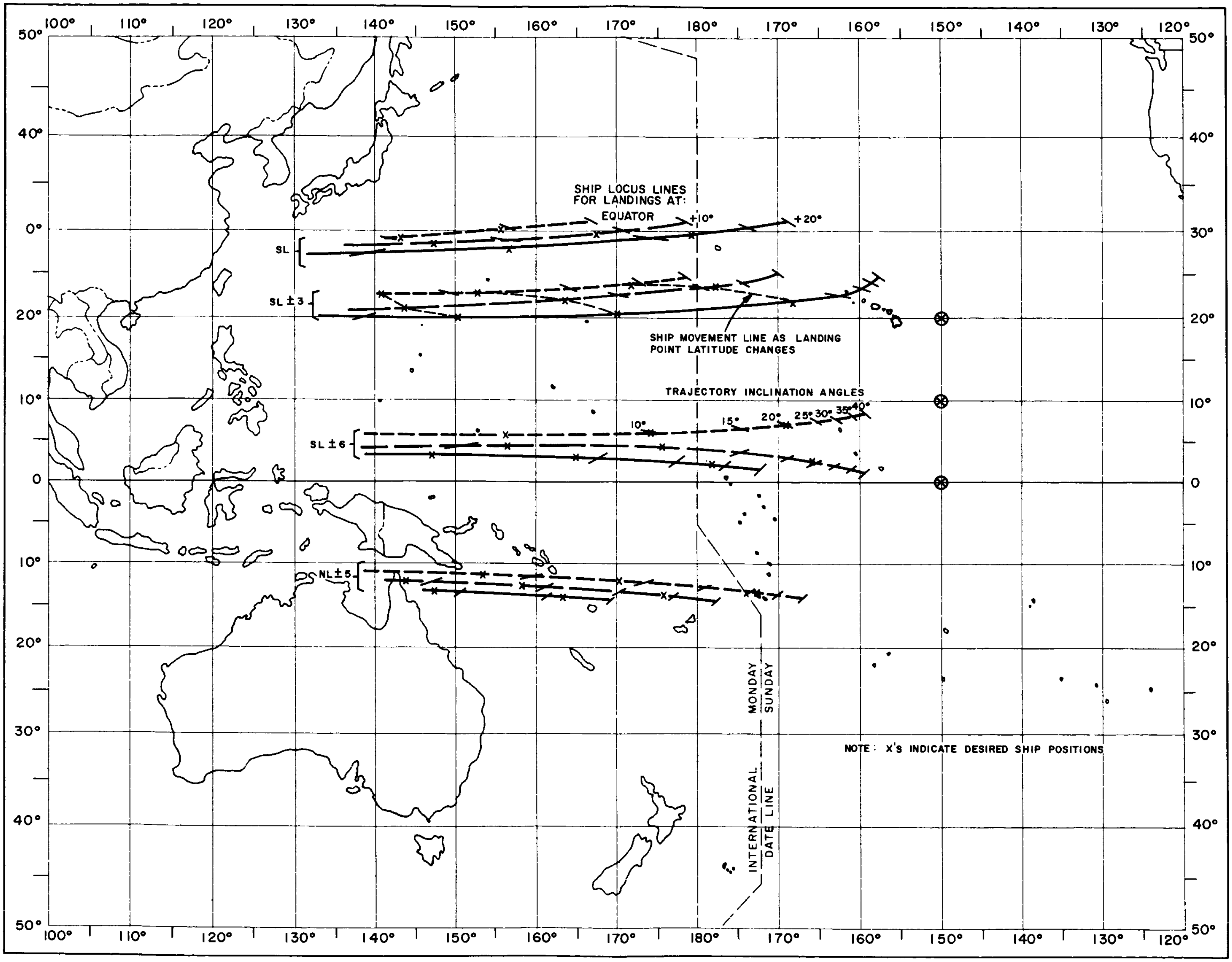

Figure 4-22. Effect on Reentry Ship Positions of Change in Landing Point Latitude

C&T INSTRUMENTATION REQUIREMENTS FOR SHIPS

The following paragraphs discuss in general terms the instrumentation requirements for ships during the reentry phase. Emphasis is on the major communication and tracking functions that a ship should be able to perform. Desired transmission range is also considered.

One of the principal factors which will influence what a ship can accomplish during the reentry phase is the reentry plasma phenomenon. Because of its significance to planning and instrumentation of a shipboard tracking and communication installation, this phenomenon is discussed first.

Reentry Plasma Effects

The plasma sheath generated by the passage of the Apollo CM through the earth's atmosphere will present communication problems of a magnitude not encountered to date in any space program. Any attempt to communicate through the plasma sheath will encounter signal reflection, attenuation, and polarization shift, atmospheric voltage breakdown between the sheath and the antenna, antenna mismatch due to the presence of the plasma, and noise generated by the plasma.

Present techniques used to estimate the magnitude of these effects are not validly applicable to an Apollo reentry. Most background work has been done with reference to missile nose cones at relatively low velocities and at zero angle of attack with reference to the vehicle body axis. The aerodynamic flow field of the Apollo vehicle will be asymmetric about all axes, because the CM will enter the atmosphere heat shield first with an angle of attack of about 35°. This is likely to generate an inhomogenous flow field with air flow separated from the afterbody of the CM and with turbulence effects present. To specify the plasma parameters which control the propagation of an electromagnetic wave at the antenna station, it is necessary to know the history of the flow field from the leading point of the shock wave to the line of sight from the vehicle antenna to the ground station. The non-equilibrium chemical kinetics of the flow field must be known to adequately specify the plasma parameters along the Apollo reentry trajectory.

Plasma research groups to date have not attempted predictions of total effective attenuation but have predicted "total blackout" regions where no propagation through the plasma is possible. This "step function" assumption appears to be reasonable for Apollo reentries since the depth of the plasma sheath and the high vehicle velocity indicate that the length of the transition region (from low attenuation to very high attenuation) will be quite short.

There seems to be general agreement among those who have attempted to predict reentry plasma effects that severe attenuation of VHF, S band, and C band* frequencies can be expected beginning shortly after the CM reaches 400,000 feet altitude, and continuing at least until the spacecraft velocity slows to about 25,000 feet per second at an altitude near 200,000 feet. (See, for example, References 6, 7, and 8.) If the spacecraft, after its initial descent, enters a ballistic lob trajectory which carries it back up above 300,000 feet, indications are that C-band, S-band, and VHF frequencies will become useful again, in that order. During the final descent in such a trajectory, VHF would be blacked out for a substantial interval, S-band for a shorter interval, and C-band might be useful throughout the descent. There does not appear to be enough experience to place much confidence in numerical values for these estimates, however.

If a nominal constant-altitude reentry trajectory or an emergency mode trajectory is flown, it is fairly certain that VHF frequencies will be blacked out through most of the trajectory, and S band through a large portion. C band should be useful once the velocity has slowed to the region of 20,000-25,000 feet per second.

These qualitative estimates of the effects of reentry plasma apply on the assumption that nothing is done to reduce signal attenuation. Recent experimental programs indicate some success in reducing signal attenuation by injecting water into the plasma (Reference 9). Generation of a magnetic field in the region of the plasma may also prove effective (Reference 10). Further tests with high-velocity, Apollo-type vehicles are necessary before predictions can be made regarding the applicability of such techniques to an Apollo reentry. Even though the techniques ultimately may prove feasible, it is questionable whether they can be developed and adequately tested in time for the earliest Apollo lunar mission.

In summary, it appears that Apollo communication and beacon signals must be assumed to be blacked out for a major portion of many of the possible reentry flight trajectories. Tracking must be planned as ionization sheath tracking at least from the reentry point until some time after the trough is reached; beacon tracking should be possible at some time during a ballistic lob trajectory. The VHF and S-band frequencies now planned for the Apollo spacecraft may or may not be useful before the final stages of descent, depending on the trajectory flown. The net result of these considerations is that shipboard instrumentation should be planned to

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*Throughout this section, the term C band is used to refer to the spectrum between 5400 and 5900 Mc, which includes the operational bands of FPS-16 and FPQ-6 radars. The term S band is intended specifically to apply to the bands 2110 to 2120 Mc and 2290 to 2300 Mc, which are the ground station transmit and receive frequencies, respectively, for which the Apollo unified tracking and communication system is being developed.

take advantage of beacon tracking and communication capabilities if they exist, but operational planning should allow for the possibility that they may not exist.

Functional Requirements for Tracking and Communication With Spacecraft

An important assumption that will be adopted is that the spacecraft equipment — particularly with regard to radio frequencies used — will be as current developments indicate. As we understand these developments, the CM will have a VHF communication system, a unified S-band tracking beacon and communication system, and a C-band tracking beacon.

The reentry plasma effects discussed in the previous section, together with other factors that are referred to shortly, indicate that reentry coverage ships ought to be capable of three modes of tracking. These are: (1) plasma sheath tracking, using C-band radar; (2) C-band transponder tracking; and (3) S-band transponder tracking.

Even optimistic estimates of plasma attenuation indicate that transponder tracking at C-band and S-band frequencies will be ineffective at least to the time that the spacecraft velocity has slowed to a near-orbital value. For those trajectories during which the spacecraft altitude does not increase significantly after orbital velocity is reached, severe signal attenuation may continue through much of the reentry trajectory. Thus, while sheath tracking is not expected to be as accurate as transponder tracking, it must be counted on to provide an earlier capability; under some circumstances, it may provide the only significant tracking capability during most of the reentry flight.

The practical reason for indicating that the radar performing sheath tracking should employ C-band rather than S-band frequencies is that the same basic radar equipment can also be used to track the C-band transponder if and when transmission conditions permit. C-band radars of the types commonly found at NASA range stations today are designed to operate in either the skin tracking (one-frequency) or beacon tracking (two-frequency) mode. In contrast, the Apollo S-band unified tracking and communication system, as it is now being developed for ground stations, could not perform sheath tracking since it is designed as a two-frequency system with tracking at the spacecraft transponder frequency as an integral feature. Furthermore, the C-band system will have a distinct advantage because its higher frequency will allow earlier transmission through the plasma.

In view of the advantages of C-band over S-band tracking during reentry, it is logical to ask whether the latter capability need be provided also. The argument justifying S-band transponder tracking capability as well develops as follows: The spacecraft's C-band transponder will have no communication capability. The S-band system will have voice, telemetry, and up-data capability. Thus, it will offer the first possible communication capability as the plasma attenuation recedes.

On the thesis that it will be desirable to provide the capability to communicate with the spacecraft if plasma effects permit, the tracking ship should have a suitable S-band antenna, radio transmitter and receiver, and other appropriate terminal equipment for two-way voice, telemetry reception, and up-data transmission. The addition of the tracking function is believed to represent a relatively small added cost. As pointed out above, it is actually a feature which is being designed as an integral part of an Apollo ground station S-band terminal. Further reasons for asking that reentry coverage ships have the S-band tracking capability are: (1) it offers a back-up tracking capability during those portions of the reentry trajectory when both C-band and S-band frequencies may be operable; and (2) spacecraft systems must operate from battery power supplies during the reentry phase; hence it may become important or necessary to limit transmissions from the spacecraft. If this is the case, the S-band system will be preferred over C-band when there is a choice, simply because the S-band system also offers the communication capability. Note that this argument does not eliminate the need for C-band radar instrumentation, but rather adds a requirement for S-band equipment; the earlier transponder tracking capability offered by the C-band frequency is still its justification.

The above paragraph has already indicated the principal reason for citing the unified S-band system as the desired communication medium during reentry: Its higher frequency will permit both earlier and longer communication capability than the alternative VHF systems. Higher spacecraft power output and more efficient modulation techniques used in the S-band system are further advantages. In view of all these factors, and noting that estimates of VHF capability indicate a very limited period of usefulness during a reentry trajectory, VHF communication equipment cannot be justified for reentry coverage.

Summarizing to this point: arguments have been advanced in support of a basic shipboard configuration consisting of a C-band radar operable in both conventional radar and transponder modes, and a unified S-band tracking and communication terminal offering: ranging, two-way voice, telemetry reception, and data transmission services. There appears to be no advantage in adding VHF capability.

Slant Range Requirement

The coverage concepts described earlier in Section 4, together with the reentry altitude profiles illustrated in Figures 4-7 through 4-11, permit an estimate of the maximum ranges for which the shipboard system should be planned. Apropos of the concept under which a ship is stationed to track the spacecraft from the time it reaches the minimum altitude in its initial descent until it flies beyond the horizon in the opposite direction, the maximum slant range tracking requirement for all trajectories included in the charts is about 485 nm. This applies in the case of the steepest reentry flight path angle and a ballistic lob trajectory after the initial descent. If the ship were stationed somewhat farther downrange so that it could track the spacecraft at the peak of a ballistic lob, the range requirement would be about 600 miles (2 db greater than 485 miles, in terms of transmission loss).

Acquisition Requirements

A few comments are in order concerning the problems of acquisition during reentry. As indicated before, sheath tracking is expected to provide the earliest capability as the spacecraft descends into the atmosphere and enters the field of visibility of the first downrange tracking ship. The signal reflected by the plasma will not be as strong as would be the signal from a transponder. Further, there may be a wake extending well behind the spacecraft, especially during the early, high-velocity portion of the reentry flight. In this case, the "target" would not be as well-defined as it would in the absence of the wake. Thus, even if the point of initial contact could be precisely predicted, it is unlikely that acquisition could be done as quickly as it could if the spacecraft's transponder were operable at this time.

An added complication is the fact that the position of the spacecraft at the time of desired acquisition may not be as accurately predictable as in earlier mission phases where the trajectory is usually ballistic. This is due particularly to the lateral maneuver capability of the vehicle. An analysis of the lateral component associated with the particular altitude profiles illustrated in the section entitled, Reentry Altitude Profiles, indicates that, for nominal reentry flights, the spacecraft would have little or no movement to either side of the straight-in path by the time it reaches the trough of the initial reentry descent. Thus, for nominal reentry trajectories, the acquisition problem should not be very severe if a tracking ship is located no more than approximately 260 miles beyond the trough, toward the landing site. If the initial reentry descent is abnormal and introduces some lateral movement, or if the ship is located a few hundred miles farther beyond the trough (perhaps to provide a longer period of tracking and communication during a ballistic lob), the spacecraft conceivably might be as much as 20 to 25 miles to one side of the straight-in path by the time it reaches the ship's horizon of visibility. In such a case, the ship would have to be able to scan over an azimuth sector of perhaps 10°.

Further study is needed of possible and probable lateral maneuver capability as a function of the reentry range traversed to be able to indicate more closely the requirements for acquisition.

Shipboard Data Processing and Communications With IMCC

Depending on the operational objectives that have been set for ships during reentry, the extent of data processing facilities provided on the ship, and the role planned for the IMCC during reentry and recovery operations, radically different requirements for ship-to-IMCC communication facilities can be arrived at. An important factor in determining the ultimate operational roles of the IMCC and the reentry ships undoubtedly will be the character of the ship-shore communications that can be assumed available in the Apollo time frame.

Reference 11 has discussed various techniques for ship-shore communications that might be appropriate for Apollo applications. Of the techniques considered, it was concluded that HF radio, communication satellite relay, and airborne relay are the only currently foreseeable possibilities worth considering. Among these, HF radio is now the primary technique in use, but suffers the handicaps of limited bandwidth and poor propagation reliability. Communication satellites are likely to provide adequate bandwidth and reliability, but the time when they will become operationally available is uncertain. Airborne relay systems are technically feasible now and offer bandwidth and reliability intermediate to that of HF radio and communication satellites; the principal problems of an airborne relay system appear to be logistical and operational.

If reliable, real-time, wideband-transmission facilities are available (e.g., by means of either space satellite relay or airborne relay), the IMCC can expect to play a very active role in coordinating reentry and recovery forces, computing the reentry trajectory and probable landing point, communicating with the astronauts, etc. On the other hand, if HF radio continues to be the primary ship-shore communication facility, less information can be transmitted back and forth, and operational planning must recognize a significant probability that ship-shore communications may fail due to propagation outages. Thus, more extensive shipboard data processing facilities probably would be required if the ship-shore communication link uses HF radio than if satellite or airborne relay communication is possible.

Section 5

REFERENCES

1. "Trajectory Studies for Use in Determining Tracking Requirements for Project Apollo," NASA Manned Spacecraft Center, August 30, 1963.

2. S. S. Dallas, "Moon-Earth Trajectories," JPL Technical Memorandum 312-239 (undated).

3. "Spacecraft Performance Specification - SID 62-51," North American Aviation, Inc., May 15, 1962.

4. "Preliminary Mission Ground Rules for Use in Apollo Mission Analysis," Mission Planning Department, Flight Operations Division, Manned Spacecraft Center, August 9, 1963.

5. J. L. Glaser, J. J. Hibbert, and P. F. Sennewald, "A Study of Instrumentation Ship Requirements for the Apollo Program," Bellcomm, Inc., September 14, 1963.

6. "Initial Report of Apollo Reentry Plasma Study," North American Aviation, Inc., SID 62-1456, January 10, 1963.

7. "Final Report on Apollo Plasma Reentry Studies," North American Aviation, Inc., SID 63-746, July 5, 1963.

8. W. B. Sisco and J. M. Fiskin, "Basic Hypersonic Plasma Data of Equilibrium Air for Electromagnetic and Other Requirements," Electromagnetic Effects of Reentry, Pergammon Press, 1961.

9. Space Aeronautics, p. 45, October, 1963.

10. H. Hodara, "The Use of Magnetic Fields in the Elimination of the Reentry Radio Blackout," IRE Proceedings, Volume 49, December 1961.

11. "Transmission Techniques for Apollo Ship-Shore Communications," Bell Telephone Laboratories, Incorporated, September 1, 1963.

Appendix A

DERIVATION OF PRE-REENTRY GROUND TRACKS

INTRODUCTION

This appendix describes the procedures used to develop ground tracks and determine spacecraft visibility from ground stations for the latter portion of lunar return trajectories, called the pre-reentry phase. This phase has been defined, for the purposes of this report, as extending from 50,000 nm altitude to an initial reentry point at 400,000 ft. Because the tracks in themselves are only of passing interest and because their application to coverage problems is not critically dependent on high accuracy, the tracks have been generated in a simple fashion. With these considerations in mind, the tracks have been developed on the basis of the assumptions listed in the following paragraph.

ASSUMPTIONS

1. The trajectory region of interest is part of a Keplerian Earth orbit.
2. The plane of the orbit is determined by the center of the Earth, the position of the landing site at time of touchdown, and a specified inclination to the Earth's equator.
3. The orbit is assumed to be elliptical, with an eccentricity generally taken to have a nominal value of 0.98.
4. The reentry flight path angle (γ_R) was generally considered to have a nominal value of -6.4°. This angle is measured between the velocity vector and the local horizontal at the initial reentry point. The negative sign indicates that the velocity vector has a component towards the Earth. The tolerances on this angle were assumed to be -5.4° to -7.4°, corresponding to the maximum design limits for heat dissipation and deceleration forces.

5. The return trip time can be made to vary from 60 to 110 hours. This spread, plus the ability to orbit the Moon longer than otherwise would be necessary, permits flexibility in choosing the time of arrival at the Earth. This insures that the landing site will be in its proper spatial orientation at the time of landing.

6. Midcourse corrections will adjust for any inaccuracies in injection so that the predicted conditions at the reentry point are obtained. In effect, such corrections will help to assure a "nominal" trajectory near Earth.

GENERAL METHOD OF ANALYSIS

The following input parameters are specified for each Moon-to-Earth trajectory: (a) the inclination of the trajectory to the Earth's equator and (b) the landing site coordinates. These parameters are sufficient to determine the trace of the trajectory plane on a stationary Earth. Next, the shape of the orbit is specified by giving: (c) the eccentricity, e, and (d) the reentry flight path angle, γ_R. The orientation of the orbit in its plane is fixed by specifying: (e) the reentry sub-point coordinates for the specified day of departure. The reentry sub-point coordinates are taken from the results of the reentry ground track analysis, described in Appendix B.

The above data are operated upon to give the ground track on a stationary Earth, together with time and altitude data for each computed point along the track. Finally, each point along the fixed-Earth track is offset by an amount depending upon its time from touchdown to give the true Earth track which takes account of Earth rotation.

STATIONARY EARTH TRACKS AND LONGITUDE OFFSETS

The first step in developing the ground track is the generation of the trace of the geocentric trajectory plane on a stationary Earth (refer to Figure A-1). The trajectory plane is oriented at an inclination I_T to the equator and made to contain the landing point, S. The latitude, λ_i, and longitude, L_i', of a point 0_i on the trace, relative to the node E, are readily found from the following equations based on right spherical trigonometry:

$$\tan L_i' = \cos I_T \tan \phi_i$$

$$\sin \lambda_i = \sin I_T \sin \phi_i \qquad \text{(A-1)}$$

The above equations permit the coordinates of the trajectory plane's trace to be plotted on a stationary Earth as functions of a parameter ϕ_i, which is the central angle measured from E, the node immediately preceding the landing site. (The

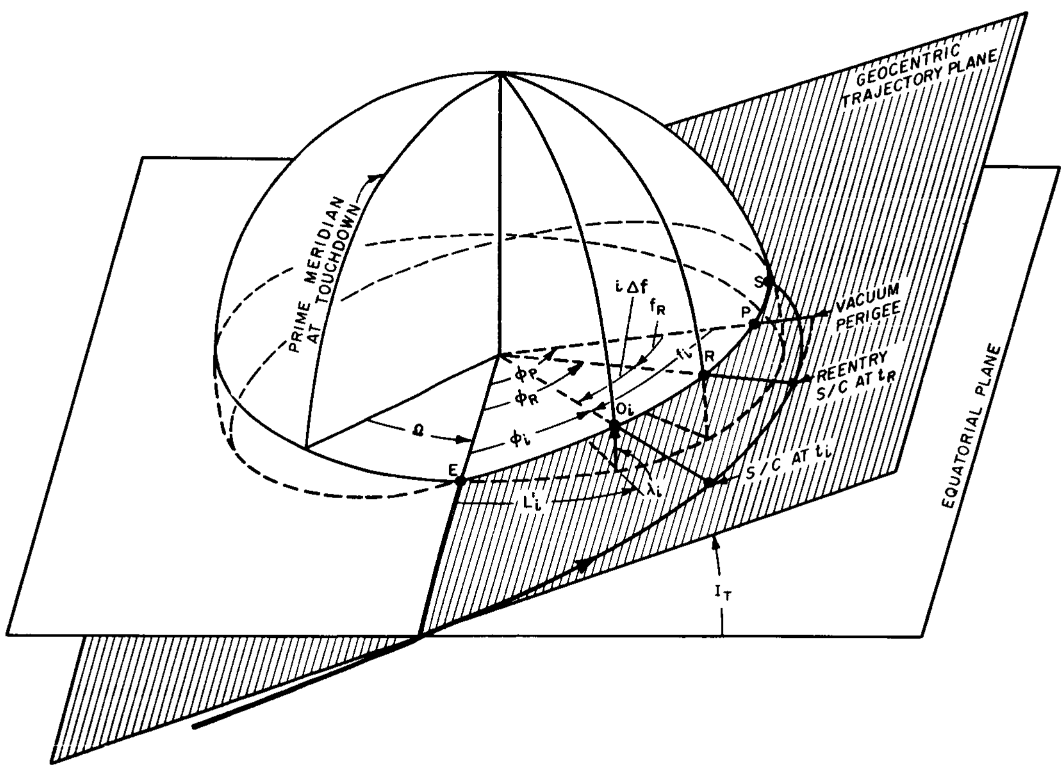


Figure A-1. Geometric Return Trajectory in Relation to Earth Fixed at Touchdown prime mark is used on the equation for longitude in order to reserve the unprimed symbol for the longitude with respect to Greenwich.) The manner in which ϕ_i is assigned a value is considered in the section of this Appendix entitled, EARTH COORDINATES OF THE GROUND TRACK.

The trace on a stationary Earth and the true Earth track derived from it (to account for the Earth's rotation) intersect at S. At all other points corresponding to times prior to touchdown, the true Earth track must be offset to the East in longitude from the stationary trace because the Earth rotates. To draw the true Earth ground track, this longitude offset must be found for each point on the stationary trace (see Figure A-2). There are two components to the offset. From reentry to touchdown, the S/C follows an aerodynamic trajectory which cannot be determined completely at this time. Accordingly, an approximate reentry point offset, α_R, as developed in Appendix B, is taken as an end-point condition. Thus, for purposes of developing the track prior to reentry, α_R may be regarded as a fixed or bias component of offset. To this must be added a variable component, $\Delta\alpha_i$, representing the displacement during the vacuum trajectory caused by the Earth's rotation in the interval $\Delta t_i = t_i - t_R$ (the time it takes the S/C to travel from the i^{th} point to the reentry point). Then $\Delta\alpha_i$ is simply $\omega_E \Delta t_i$, where ω_E, the Earth's angular velocity, is 0.25068°/min.

The total longitude offset (in degrees) is:

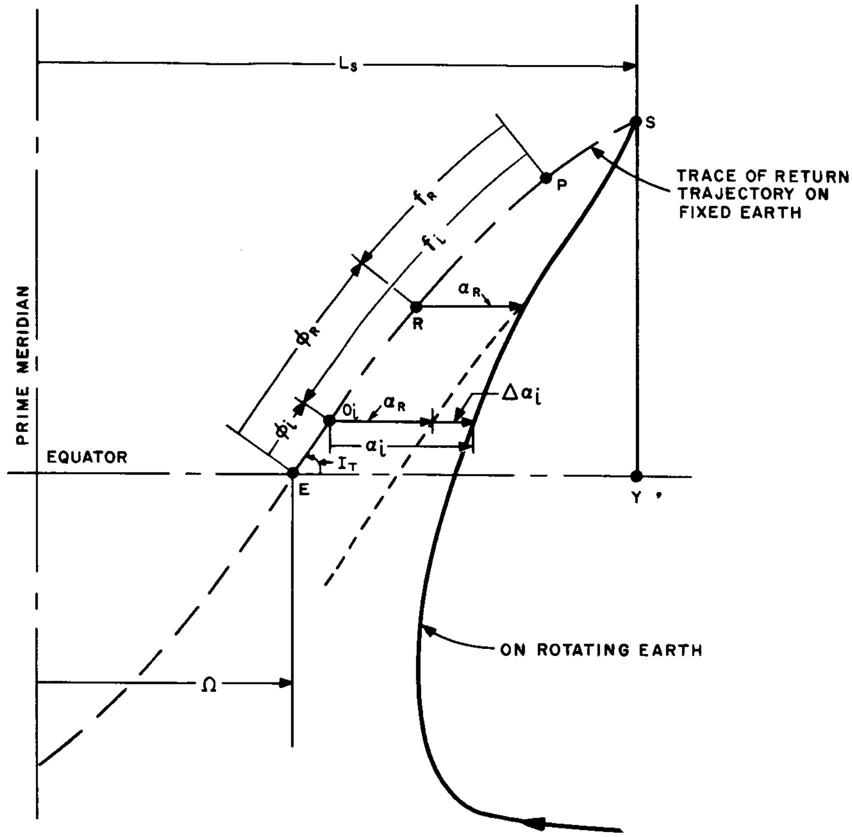
$$\alpha_i = \alpha_R + \omega_E \Delta t_i \tag{A-2}$$

THE TIME-POSITION RELATIONSHIP

The time-position relationship for a body in Keplerian motion is well documented. This appendix, therefore, only indicates equations of interest used in the computation of Δt_i without deriving them.

For the moment, it is assumed that the orbit is completely specified. (It is pointed out that only the inclination of the plane and the condition that it pass through the landing site have been specified thus far.) We seek the relationship between S/C position (expressed in terms of angular position with respect to an arbitrary reference point) and the time it occupies this position (see Figure A-3). For computational purposes, time is most readily expressed as a function of an angular parameter called eccentric anomaly.*

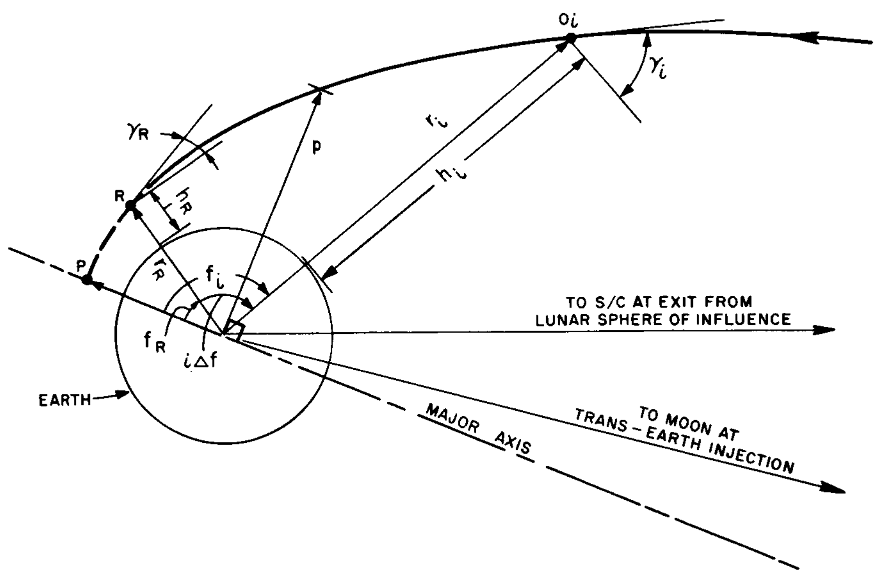
*The word "anomaly" in celestial mechanics is used to denote angular measurement from perigee. "True anomaly" is the angle measured at the focus between the point of interest and perigee. "Eccentric anomaly" has a more involved definition which will not be stated here but may be found in any celestial mechanics text.



LEGEND:

O_i	GENERAL POSITION OF S/C	Ω	LONGITUDE OF NODE AT TOUCHDOWN
R	REENTRY POINT	ϕ_i	CENTRAL ANGLE (FROM NODE)
S	LANDING POINT	f_i	TRUE ANOMALY (FROM PERIGEE)
P	VACUUM PERIGEE	α_i	OFFSET IN LONGITUDE
E	NODE PRECEDING S	$\Delta\alpha_i$	INCREMENTAL OFFSET PRIOR TO REENTRY
L_s	LONGITUDE OF LANDING SITE		

Figure A-2. Development of Return Ground Track Using Offsets



LEGEND:
- O_i - GENERAL POSITION OF S/C
- P - VACUUM PERIGEE
- R - REENTRY
- γ - FLIGHT PATH ANGLE (ANGLE BETWEEN TANGENT AND NORMAL TO RADIUS VECTOR, POSITIVE IN DIRECTION OF INCREASING r)
- f - TRUE ANOMALY
- p - SEMI-LATUS RECTUM
- h - HEIGHT ABOVE EARTH
- r - RADIUS VECTOR
- i - INDEX DENOTING GENERAL (i^{th}) COMPUTATIONAL INTERVAL

Figure A-3. Lunar Return Ellipse

$$t_i = \frac{\tau}{2\pi}\left(E_i - e \sin E_i\right) \tag{A-3}$$

where

t_i is the time to traverse the distance from the i^{th} position to perigee* along the orbit

E_i is the eccentric anomaly associated with t_i

e is the eccentricity of the ellipse

τ is a constant peculiar to the ellipse being traversed:

$$\frac{\tau}{2\pi} = \left[\frac{r_P}{1 - e}\right]^{3/2} \frac{1}{\sqrt{k}} \tag{A-4}$$

where

r_P is the perigee distance of the ellipse (found from Equation A-9)

k is the universal gravitational constant

$= 1.40776 \times 10^{16}\ ft^3/sec^2$

$= 2.25921 \times 10^{8}\ nm^3/min^2$

$$\frac{1}{\sqrt{k}} = 0.00006653 \frac{min}{nm^{3/2}}$$

But the S/C position is more conveniently given in terms of true anomaly, f_i, which is related to eccentric anomally, E_i, by:

$$\tan \frac{E_i}{2} = \sqrt{\frac{1 - e}{1 + e}} \tan \frac{f_i}{2} \tag{A-5}$$

The procedure for finding t_i vs. f_i is then:

1. Choose an eccentricity e appropriate to the return conditions. (For Apollo Earth-Moon trajectories, the eccentricity should lie between about 0.95 and 0.995.)
2. Assign a value to f_i. (In a computing routine, f_i will assume successive values as indicated below.)

---

*"Perigee" is indicated in Figures A-1 and A-3 by the point P lying on the major axis of the ellipse. The S/C will not actually traverse the elliptical arc RP since aerodynamic effects following reentry will cause the trajectory to deviate from a Keplerian path. It is still convenient to refer to perigee in return and reentry trajectories, where perigee is now defined as the point of closest approach in the absence of an atmosphere. It is often known as "vacuum perigee."

3. Compute E_i via Equation A-5

4. Compute t_i via Equation A-3 and Equation A-4.

Only that portion of the trajectory prior to reentry (where $f_i > f_R$) is of present concern in generating the tracks. Therefore, all variables are expressed with respect to the reentry point R:

$$f_i = f_R + i\Delta f \tag{A-6}$$

where Δf is an arbitrary, specified computing interval, and f_R, the true anomaly of the reentry point, has yet to be determined. The other dependent reentry parameters are found as follows:

1. E_R, the eccentric anomaly at reentry,

$$\tan \frac{E_R}{2} = \sqrt{\frac{1 - e}{1 + e}} \tan \frac{f_R}{2}$$

2. t_R, the time from reentry to vacuum perigee,

$$t_R = \frac{\tau}{2\pi} (E_R - e \sin E_R).$$

Then $\Delta t_i = t_i - t_R$.

THE GEOCENTRIC CONIC

The gap in the above discussion is now filled by determining the parameters of the geocentric ellipse. This will permit finding f_R, the true anomaly at reentry, and r, the position vector of the S/C throughout the latter part of the vacuum trajectory.

The quantities assumed to be known are:

1. The altitude at reentry, $h_R = 400{,}000$ ft.
2. The flight path angle at reentry, γ_R
3. The eccentricity of the ellipse, e.

(In general, e and γ_R will not be known exactly but will be confined to narrow ranges, namely $0.95 \le e < 1.0$ and $5.4° \le |\gamma_R| \le 7.4°$.

The symbols used in the following derivation are identified in Figure A-3.

The general equation of a conic is

$$r = \frac{p}{1 + e \cos f}. \tag{A-7}$$

where p is the semi-latus rectum.

$$\therefore \frac{dr}{df} = \frac{pe \sin f}{(1 + e \cos f)^2} = \frac{r^2 e \sin f}{p}$$

and

$$\tan \gamma = \frac{1}{r} \frac{dr}{df} = \frac{re \sin f}{p} \tag{A-8}$$

We wish to eliminate r between Equation A-7 and Equation A-8. From Equation A-8,

$$\sin f = \frac{p}{r} \frac{\tan \gamma}{e}$$

$$\therefore \cos f = \sqrt{1 - \frac{p^2}{r^2} \frac{\tan^2 \gamma}{e^2}}$$

From Equation A-7,

$$\frac{p}{r} = 1 + e \cos f$$

$$= 1 + e \sqrt{1 - \frac{p^2}{r^2} \frac{\tan^2 \gamma}{e^2}}$$

Solving for $\frac{p}{r}$,

$$\frac{p}{r} = \cos^2 \gamma \pm \cos \gamma \sqrt{e^2 - 1 + \cos^2 \gamma}$$

whence

$$p = r \left[\cos^2 \gamma \pm \cos \gamma \sqrt{e^2 - 1 + \cos^2 \gamma}\right]$$

where r and γ are given at the same point.

Since

$$r = r_E + h,$$

then

$$r_R = r_E + h_R,$$

and

$$p = (r_E + h_R) \left[\cos^2 \gamma_R \pm \cos \gamma_R \sqrt{e^2 - 1 + \cos^2 \gamma_R}\right]$$

The plus sign for the radical should be taken for the evaluation of p since it gives, for a parabola (e = 1), $p = 2r \cos^2 \gamma$, which is correct. Thus the conic is determined.

Returning to the equation of the conic,

$$r = \frac{p}{1 + e \cos f}$$

and now knowing p and e, r_P may be found at f = 0 as

$$r_P = \frac{p}{1 + e} \qquad \text{(A-9)}$$

Also

$$\cos f_R = \frac{1}{e}\left[\frac{p}{r_R} - 1\right] \qquad \text{(A-9a)}$$

Now the radius vector of the general point may be determined:

$$r_i = \frac{p}{1 + e \cos f_i} \qquad \text{(A-10)}$$

and the altitude,

$$h_i = r_i - r_E \qquad \text{(A-11)}$$

where r_E is the Earth's radius.

EARTH COORDINATES OF THE GROUND TRACK

To find the true Earth coordinates, L_i and λ_i, it remains only to relate the true anomaly, f_i, to the central angle, ϕ_i, relative to the node, which appears in Equation A-1. It is clear from Figures A-1 and A-2 that

$$\phi_i = \widehat{ER} + f_R - f_i$$

and solving for $f_R - f_i$ in Equation A-6, we have

$$\phi_i = \widehat{ER} - i\Delta f$$

where $\widehat{ER}$ is given data (obtained from the reentry calculations described in Appendix B).

Figure A-2 also shows that the longitude of the node at the time of touchdown is

$$\Omega = L_s - \widehat{EY}$$

where L_s is the longitude of the landing site and $\widehat{EY}$ is its incremental longitude from the node, obtained, again, from the associated reentry program.

Finally, the true Earth coordinates are

$$L_i = L_i' + \Omega + \alpha_i$$

$$\lambda_i = \sin^{-1}\left[\sin L_T \sin \phi_i\right]$$

Examples of pre-reentry ground tracks generated by the method described here are included at the end of this Appendix in Figures A-6 through A-9.

VISIBILITY CONSIDERATIONS

Having developed the ground track, the next question of interest is the visibility of the S/C (or lack of it) from ground stations (Refer to Figure A-4). The visibility angle θ_i is defined as the angle between the S/C and the limit of S/C visibility at its corresponding altitude, measured at the center of the Earth, and is

$$\theta_i = 90 - \psi - \nu_i$$

where ψ is the minimum elevation angle (masking angle) of the station antenna, and ν_i, from the law of sines, is found to be

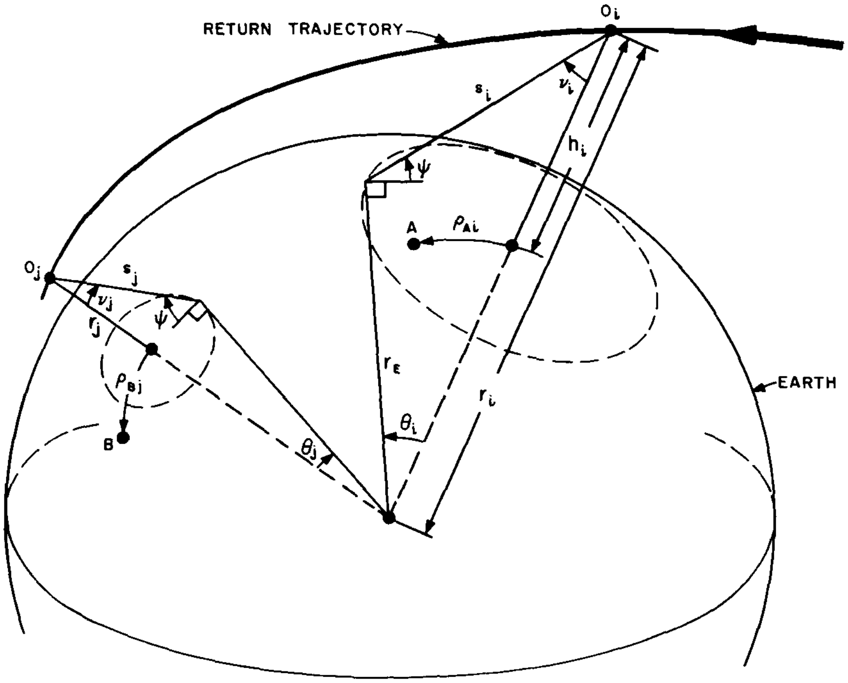
$$\nu_i = \sin^{-1}\left[\frac{r_E \cos \psi}{r_i}\right]$$

The slant range to a station at the visibility extreme is

$$s_i = \left[r_i^2 + r_E^2 - 2r_E r_i \cos \theta_i\right]^{1/2}$$

For a given location of a station, it is now possible to determine the limit of its visibility along the track by matching the visibility angle, θ_i, at a ground track point to the station separation angle, ρ_i (the angular separation of the station from that point). One way of doing this by a cut-and-try process is indicated in Figure A-5. θ_i's associated with specific track points are marked on the track. From a given station location as center, arcs of small circles are drawn with radii ρ, representing different angular distances.* At the track point at which $\rho = \theta_i$, the station can just see the S/C. In general, each station will have two such points near the Earth, the more distant one corresponding to initial sighting as the S/C rises above the horizon and the nearer one corresponding to loss of visibility below the horizon. In the computer program which has been developed, an interpolation routine embodying the same visibility criterion as described above is employed. Here

*On the map projections commonly used, the locus of points of equal separation from a station would not be circles.



LEGEND: ψ - MINIMUM ELEVATION ANGLE OF STATION (ASSUMED 5°)

θ_i - VISIBILITY ANGLE (LIMIT OF SEPARATION OF STATION FROM S/C SUBPOINT FOR WHICH S/C AT HEIGHT h_i IS VISIBLE). GENERATES CIRCLE OF VISIBILITY ABOUT SUBPOINT

ν_i - ANGLE BETWEEN r_i AND LINE TO CIRCLE OF RADIUS θ_i

s_i - SLANT RANGE FROM S/C TO CIRCLE OF RADIUS θ_i

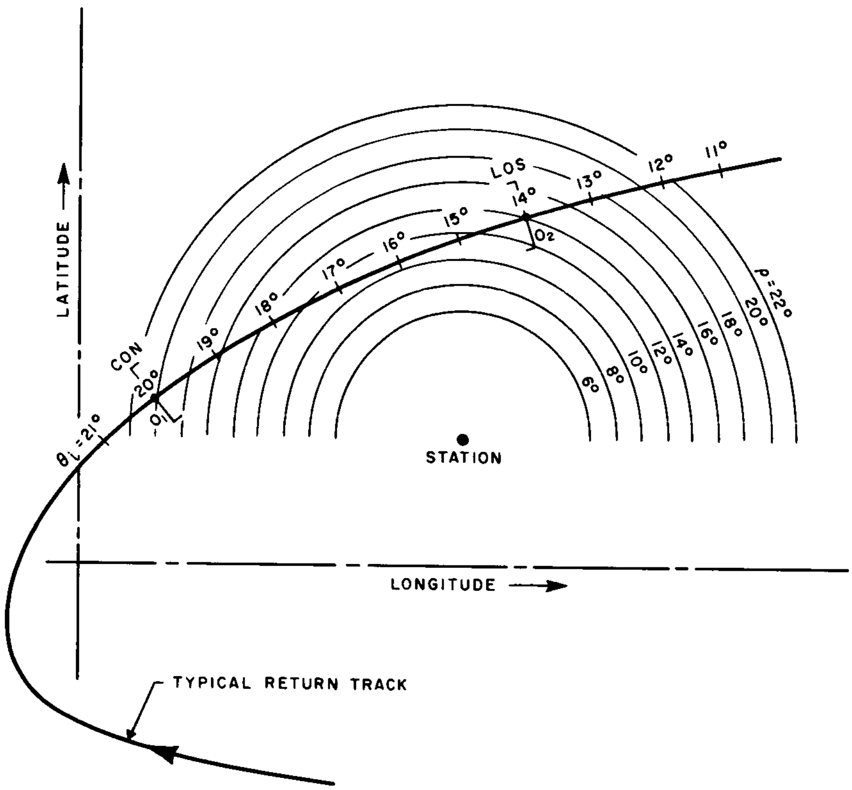
ρ_{xi} - ANGULAR SEPARATION OF STATION AT X FROM SUBPOINT OF S/C AT O_i

VISIBILITY CRITERION: STATION X CAN SEE S/C AT O_i WHEN $\rho_{xi} \leq \theta_i$

E.G.: A CAN SEE S/C AT O_i SINCE $\rho_{Ai} < \theta_i$

B CANNOT SEE S/C AT O_j SINCE $\rho_{Bj} > \theta_j$

Figure A-4. Circles of Visibility Along Ground Track



LEGEND: θ_i - COMPUTED VISIBILITY ANGLE TO S/C AT INDICATED POINT ON TRACK
ρ - RADIUS (IN DEGREES OF GREAT CIRCLE ARC) OF CIRCLE ABOUT STATION
O_1 - POINT OF INITIAL VISIBILITY ($\rho_1 = \theta_1 = 20°$) DESIGNATED CON
O_2 - POINT OF LOSS OF VISIBILITY ($\rho_2 = \theta_2 = 14°$) DESIGNATED LOS

Figure A-5. Portion of Track Visible from a Given Station

ρ_{xi}, the separation of station x from the i^{th} point along the track, is computed from the following expression:*

$$\cos \rho_{xi} = \cos (L_i - L_x) \cos \lambda_i \cos \lambda_x + \sin \lambda_i \sin \lambda_x .$$

PRE-REENTRY COMPUTER PROGRAM

The relationships given in this appendix have been incorporated into a computer program which was used to develop coordinates for the pre-reentry ground tracks, and visibility limits presented in this report.† In addition, the SC-4020 recorder‡ was used to provide automatic plots of the ground track data. To accomplish this, it was necessary to transform the latitude coordinate so as to be compatible with the Miller projection used on the maps. The Miller projection is a modified Mercator projection which maps a point at latitude λ_i degrees to one with a North-South displacement from the equator equivalent to

$$y_i = \left\{ 1.25 \ln \left[\tan \left(45° + \frac{2|\lambda_i|}{5} \right) \right] \right\} \frac{360}{2\pi} \text{ degrees of longitude.}$$

This transformation was included in the automatic plot routine.

VARIATION OF PRE-REENTRY GROUND TRACK WITH INPUT PARAMETERS

Figure A-6 shows a combined pre-reentry and reentry track computed for the following nominal conditions:

1. Landing site at San Antonio, Texas (latitude 29.5° north, longitude 99° west)
2. Departure of the spacecraft from the Moon at Southern Lunstice, the Moon's declination with respect to the Earth's equator being -28.5° at this time
3. Trajectory inclined 29.5° to equator (this, in conjunction with the latitude of the landing site, results in a due-east approach heading at the landing site

*This is the equation for a small circle on a sphere. The circle has its center at L_x, λ_x and radius ρ_{xi} in degrees of great circle arc. The points on the circle have coordinates, L_i, λ_i.

†In practice, it was necessary to run the reentry program first and then utilize some of the results as inputs to the pre-reentry program.

‡The SC-4020 microfilm recorder generates the plot on 35 mm film aperture cards. These cards are then fed to a Xerox 1824 printer which produces black-on-white positive prints, expanded to the scale of the maps with which they are used. The maps are overlaid on the plots which are then traced on the maps by hand.

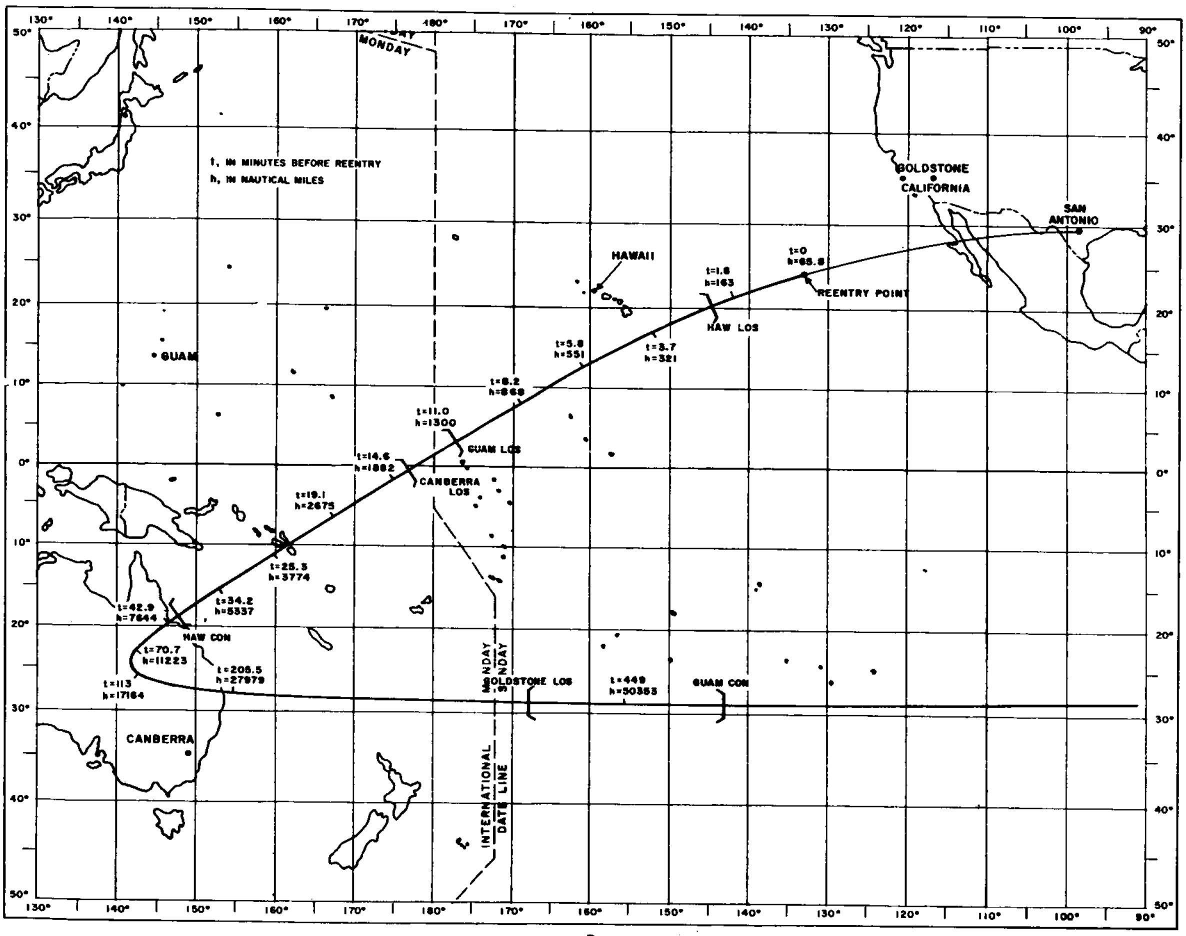


Figure A-6. Example of Pre-Reentry and Reentry Track

4. Reentry flight path angle = 6.4°

5. Orbit eccentricity = 0.98

Altitude and time ticks have been added to Figure A-6 from the trajectory data available on the computer printout. In addition, visibility acquisition and loss have been indicated for a number of stations, with antenna masking angles of 5°. This trajectory, like all the pre-reentry trajectories developed for this report, terminates at the reentry point. However, the reentry track developed in Appendix B for the same lunar-departure conditions has been appended to illustrate the continuity of the two phases.

In Figures A-7 through A-9, one parameter at a time is changed, all others being held fixed, to show the effect of such variation.

In Figure A-7, the effect of variation in departure time is illustrated. In this analysis, a change in the departure day produces a shift in the position of the reentry point along the fixed Earth trace. Since the reentry altitude is assumed fixed, this shift merely rotates the return ellipse in its plane and causes the change in the true Earth track as shown. For all the tracks in Figure A-7, the corresponding altitude and time ticks have been placed at the same values of true anomaly to illustrate the fact that the shape of the trajectory remains unaltered. The tracks shown are those for departure from the Moon at SL, SL ± 2 days, and SL ± 4 days.

The effect of variation in trajectory inclination is shown in Figure A-8. Here also, as in the variation of departure day, the time-position relationship of the trajectory, as it is referred to its origin, remains unchanged. This is again reflected in the identical time-altitude ticks for the same values of true anomaly on the several tracks. The Earth track changes markedly, however. The effect of variation in these two parameters (day of departure and trajectory inclination angle) is of particular interest in the analysis discussed in Section 4 of the main body of this report.

In Figure A-9, the eccentricity of the orbit is varied between 0.96 and 1.0. The effect of variation in e is to change the shape of the trajectory. (See the equation on page   for the semi-latus rectum "p", which depends only on e and γ_R when the reentry altitude is fixed.) The effect of this change is not great in the vicinity of reentry, but at the longer ranges, the tracks diverge increasingly. The greatest effect is in the altitude profiles; this, in turn, affects the visibility capability of the stations. Because there is no way of knowing the value of e that will be used for any given return trajectory at this time (and in any event the effects of such a variation appear small in the regions of the pre-reentry tracks of most interest here), all trajectories used in the pre-reentry coverage analysis have been computed with the nominal value of e = 0.98.

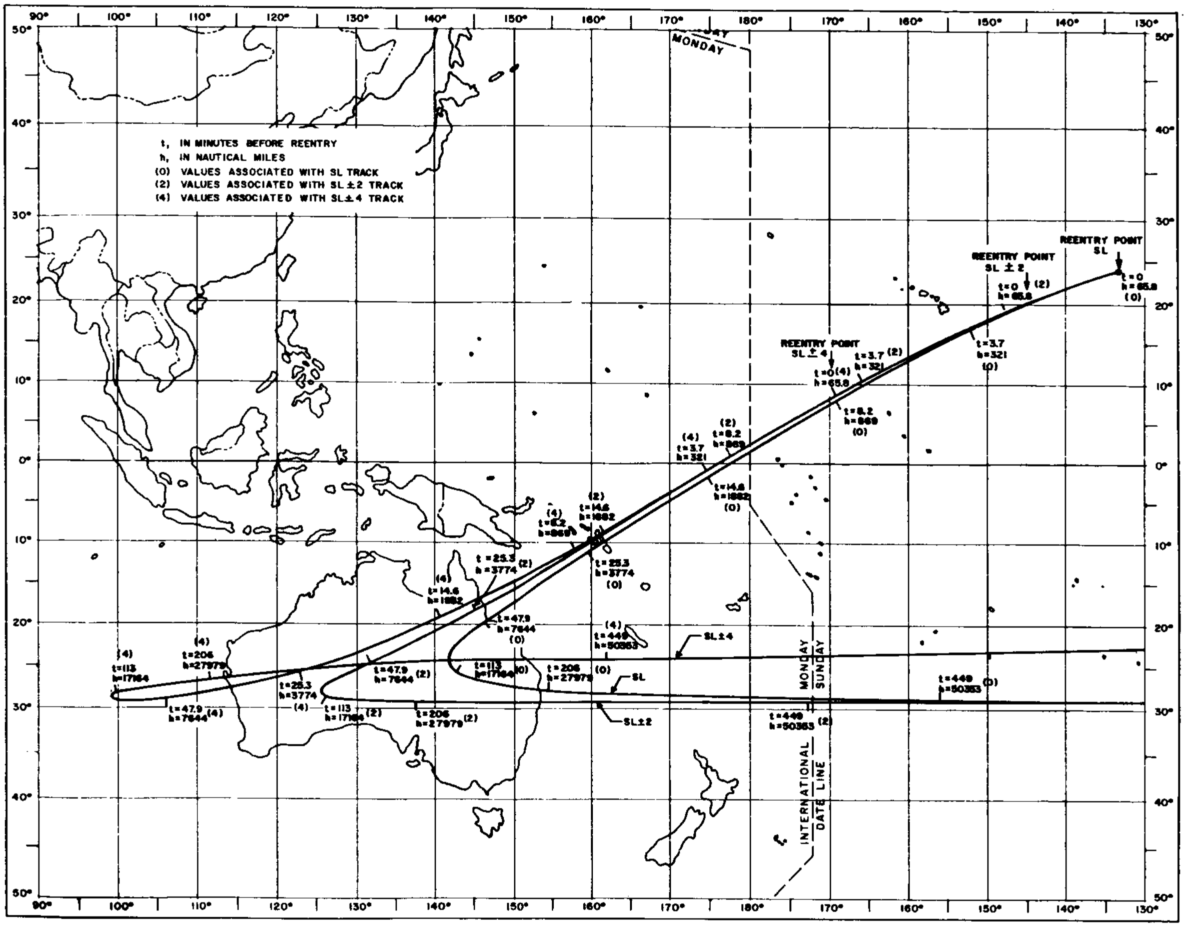


Figure A-7. Effect on Pre-Reentry Track of Variation in Departure Time

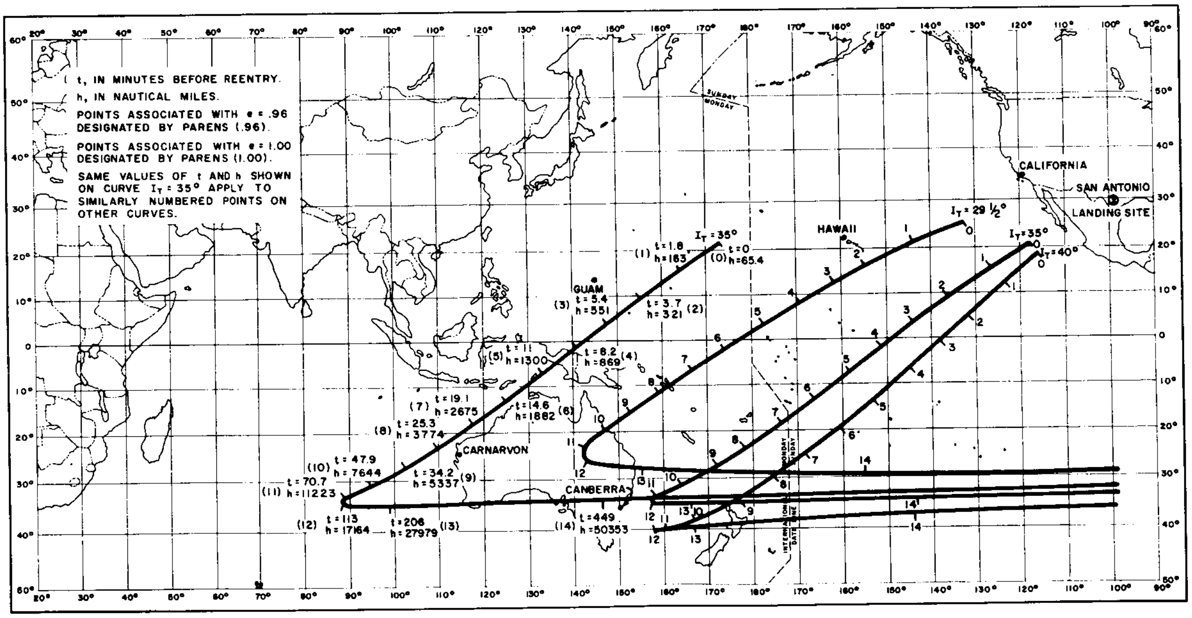


Figure A-8. Effect on Pre-Reentry Track of Variation in Trajectory Inclination

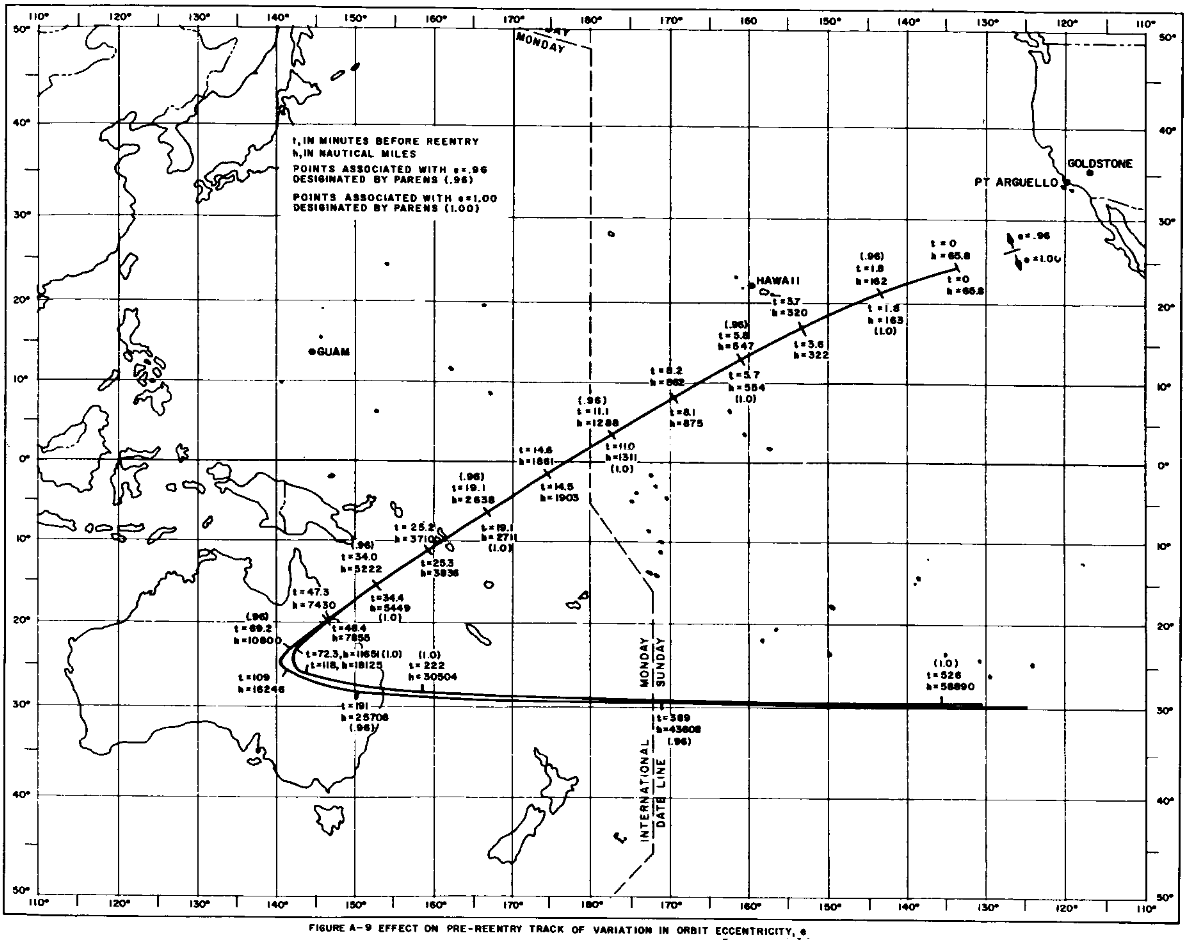


FIGURE A-9 EFFECT ON PRE-REENTRY TRACK OF VARIATION IN ORBIT ECCENTRICITY, e

Figure A-9. Effect on Pre-Reentry Track of Variation in Eccentricity

The effect of variation in γ_R has not been illustrated because no appreciable separation of tracks for different conditions occurs even though the altitude profiles are quite distinct. Two effects are produced. First, a change in the shape of the ellipse results through the expression for p, as it does for a change in eccentricity. Secondly, a change in γ_R is related to a change in sweep angle from the Moon to reentry.* It follows that a 1° change in γ_R will then change the position of the reentry subpoint by 2° about the nominal. As in the case of e, a nominal value of -6.4 for γ_R is used for the pre-reentry coverage analysis.

*See Appendix B

Appendix B

DERIVATION OF REENTRY GROUND TRACKS

INTRODUCTION

This section develops the equations used to generate the reentry ground tracks presented in this report. The solution is based upon a simplified model of the trajectory geometry, which is considered accurate enough for the purposes of the study. The assumptions on which the model is based are discussed in the section below.

ASSUMPTIONS

1. The reentry trajectory lies in the same plane as the pre-reentry trajectory. This plane contains the Moon at departure, the center of the Earth, and the landing site at touchdown. Alternatively, the plane may be defined by specifying its inclination I_T to the Earth's equator and again demanding that it contain the centers of the Earth and the Moon.
2. The reentry flight path angle γ_R was generally considered to have a nominal value of -6.4°. (See Assumption 4 in Appendix A.)
3. The "sweep angle" from the Moon to the reentry point will be 161.2°. This angle is measured between a line from the center of the Earth to the center of the Moon at the time of departure from the lunar parking orbit and a line from the center of the Earth to the reentry point. The assumed value follows from the approximation $S = 180° - \theta - |2\gamma_R|$. This relationship states that the major axis of the trajectory is offset by $\theta°$ from the Earth-Moon line at the time of trans-Earth injection, and the true anomaly at reentry is approximately 2γ (an exact value for parabolic trajectories) (see Figure A-3). The average value of θ for a large range of trajectories is 6°. With a nominal γ_R of -6.4°, S = 161.2°.

4. The reentry range may vary from 1200 nm to 5000 nm. This range is defined as the length of the ground track measured on a rotating Earth from the initial reentry to touchdown.

5. The horizontal velocity over the entire reentry phase to a point 50,000 feet above the Earth is assumed constant (though different for different length reentry paths) at a value derived from reentry trajectories in Reference 1.

6. The maximum declination of the moon throughout any lunar cycle applicable to the data derived here is 28.5°.

Because some of the above assumptions may appear unduly restrictive and artificial, the basis for their adoption will be amplified. With regard to Assumption 1, there is no difficulty justifying the approximation that the reentry trajectory lies in a geocentric plane (excluding the effect of lateral maneuvers). This is plane MGS in Figure B-1. In fact, a patched conic model, which would be a closer representation of the true trajectory than that presented here, assumes that the entire return trajectory beyond the LSOI (Lunar Sphere of Influence) lies in a geocentric plane. The assumption, however, that the reentry trajectory plane also contains the center of the Moon at departure is clearly not strictly true, except in the rare co-planar case in which the entire trajectory lies in the Earth-Moon plane. (Again, referring for comparison to the patched-conic model, the geocentric trajectory plane contains, instead, the exit point, E, on the LSOI.) Nevertheless, owing to the distances involved, the trace of the geocentric plane determined by the patched-conic model, EGS, and that of the single plane model used here, MGS, are close to each other and to the trace of the true trajectory as well, especially in the region from reentry to touchdown. The reentry track developed here is, moreover, only the average position of the true track, as a consequence of the inevitable lateral maneuvers which the S/C must perform. However, the actual lateral motion for nominal reentries will be small and will not materially affect the conclusions based on the longitudinal straight-in track.

With regard to Assumption 3, as a consequence of the variable times of flight, as well as other factors, the true reentry points, R, will lie at different angular distances MR from the trajectory origin. However, the variation in reentry point location for a 24-hour spread of times of flight, other conditions being equal, is only of the order of 5° (see Reference 2).* In order to limit the number of computations of reentry points to manageable proportions, this study has assumed a fixed angular separation (161.2°) of the reentry point from the lunar sub-point at departure, independent of the time of flight. A plot of the locus of R for the multiplicity of

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*All References are listed on pages 5-1 and 5-2.

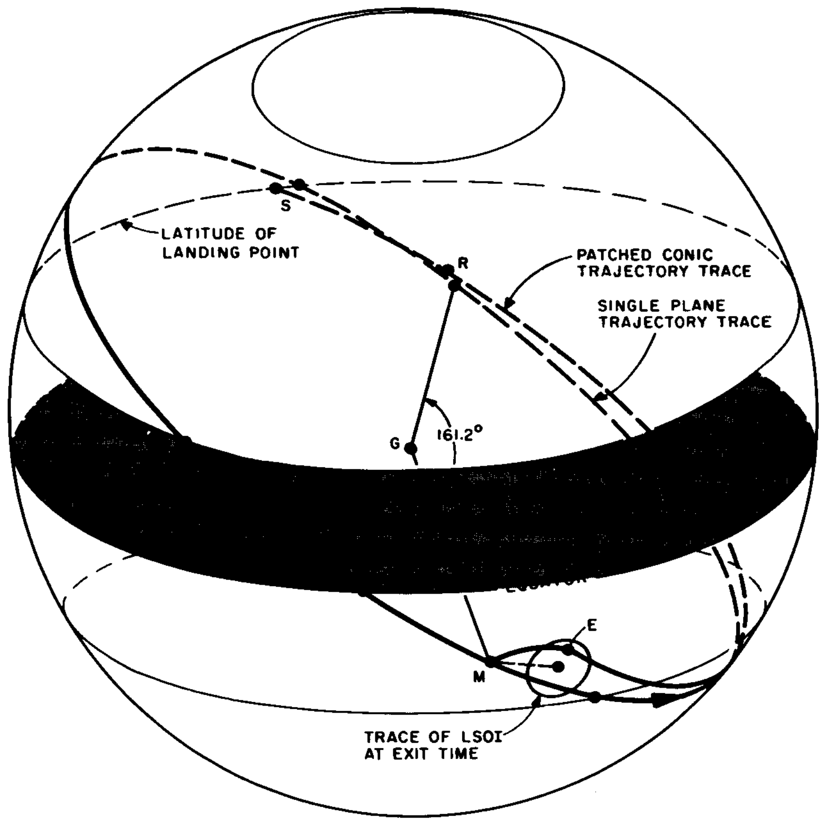

Figure B-1. Return Trajectory Geometry

conditions of interest on all possible mission dates would yield no more information that the nominal position of R presented here, with knowledge of its uncertainty. Thus, while in actual missions, a precise calculation of the reentry point would be necessary to determine the optimum position for a ship tracking station, this is not needed to establish the broad requirements for numbers and movement of ships to which this study is addressed.

The value for the maximum declination, $\lambda_{M_{max}}$, of the Moon taken in Assumption 6 is applicable to the period of intended launch. Results will change as $\lambda_{M_{max}}$ changes.

SOLUTION OF REENTRY GEOMETRY

Stationary Earth Trace

The solution of the reentry trajectory model is based upon the spherical geometry shown in Figures B-1 and B-2. Figure B-1 shows the trace on a stationary Earth of the plane in which the trajectory is assumed to lie. Figure B-2, in which the trace is unfolded, depicts all possible configurations for the return geometry. In Figure B-2a, the trajectory trace at departure from M, at latitude λ_M, lies in a northeasterly direction, while in Figure B-2b, the initial direction of the trace is southeast, corresponding to the situation shown in Figure B-1. The inclination of the trajectory plane to the equator, I_T, and the day of departure, specified by λ_M* (the latitude of the Moon) are given. Also given is the latitude λ_S of the landing site S, which lies on the trajectory trace. Desired are the coordinates of the reentry point R and the ground track of the reentry trajectory. First the track is determined on a stationary Earth; then offsets are applied which yield the track on a rotating Earth. Standard spherical trigonometry relationships are used throughout.

The position of departure, $\overset{\frown}{XM}$, is first determined relative to the nearest equator crossing, X, on the stationary Earth trace (See Figure B-2):

$$\sin \overset{\frown}{XM} = \frac{\sin \lambda_M}{\sin I_T}$$

(A negative value of $\overset{\frown}{XM}$ means M is to the left of X.)

*The latitude of the Moon, λ_M, varies approximately sinusoidally over the lunar month. For convenience, in referring to the time of departure, the latitude values have been quantized to correspond to 26 discrete positions of the Moon which have been called "days 0 to 6" from lunstice, northern or southern. In addition, the Moon's position at latitude 0° is called "node." Since λ_M is the same for days symmetrically spaced either side of lunstice, a given position of M at departure may be referred to, for example, as S. L. ±3, meaning the latitude associated with the Moon's position 3 days either side of southern lunstice.

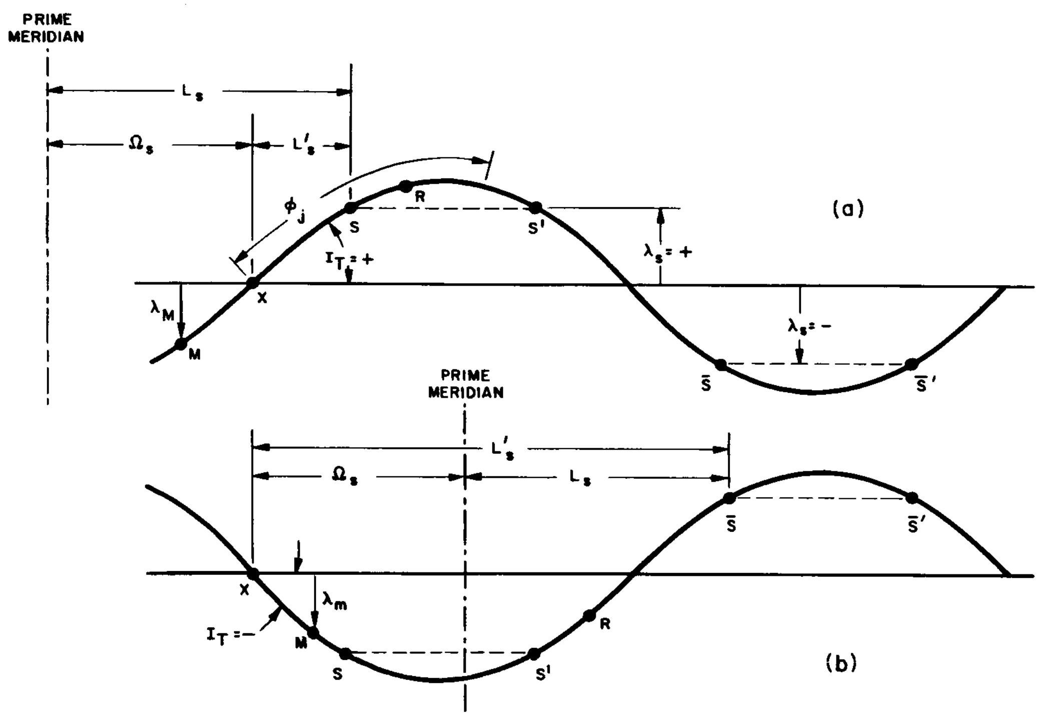

Figure B-2. Trace of Trans-Earth Trajectory on Stationary Earth

Then the position of the reentry point, R, is found at the fixed separation $\widehat{MR} = 161.2°$ from M:*

$$\widehat{XR} = \widehat{XM} + 161.2°$$

The reentry range $\widehat{RS}$ is found after the position $\widehat{XS}$ of the landing site has been determined:

$$\sin \widehat{XS} = \left| \frac{\sin \lambda_S}{\sin I_T} \right|$$

Note in Figure B-2 that, depending on the direction of approach, the direction of departure (sign of I_T), and the hemispheric location of S (sign of λ_S), S is given a different symbol, and $\widehat{XS}$ may have to be modified accordingly, thus:

$$\widehat{XS'} = 180° - \widehat{XS}$$

$$\widehat{X\bar{S}} = 180° + \widehat{XS}$$

$$\widehat{X\bar{S}'} = 360° - \widehat{XS}$$

Then $\widehat{RS}$ (or $\widehat{RS'}$, etc.) = $\widehat{XS} - \widehat{XR}$.

Next, to develop the entire ground track, the coordinates of points between R and S are determined:

$$\text{let } \phi_j = \widehat{XR} + j\Delta f$$

where Δf is a specified computing interval chosen to yield track points suitably close together.

The latitude λ_j and longitude L_j' of the point defined by ϕ_j, relative to X, are given by

$$\sin \lambda_j = \sin I_T \sin \phi_j$$

$$\tan L_j' = \cos I_T \tan \phi_j$$

In the foregoing, it is assumed that the landing site approach heading and the departure heading have been properly selected for a given landing site to provide an admissible reentry range $\widehat{RS}$.

Offsets and Rotating Earth Track

Finally, the ground track on the rotating Earth is determined. From computer runs of the reentry trajectory, the time from reentry to 50,000 ft. above the

*The position of R relative to S as determined by $\widehat{MR}$ makes some tracks inadmissible, e.g., the case where S precedes R or where $\widehat{RS}$ is either too short or too long.

Earth was found to be approximately a linear function of the reentry range. Therefore a straight line was fitted to the data:

$$t_{\widehat{RS}} = a\ \widehat{RS} + b$$

where

$\widehat{RS}$ is measured in degrees

$a = 0.24$

$b = 2.7$

$t_{\widehat{RS}}$ is measured in minutes.

The velocity was assumed to be constant from reentry to 50,000 feet altitude. (The data in Reference 1 shows that for reentry ranges greater than about 2000 nm, this approximation is fairly good, while for shorter ranges the offset is in any event not great.) Then t_j, the time to termination from intermediate points, is proportional to the separation of these points from S:

$$t_j = \left[\frac{\widehat{RS} - j\Delta f}{\widehat{RS}}\right] t_{\widehat{RS}}$$

Now the offset α_j for all points on the reentry track can be found:

$$\alpha_j = \omega_e t_j$$

where ω_e is the Earth's rotational speed.

This offset is added to the stationary Earth trace as a longitudinal displacement to the east. From the 50,000 feet altitude to touchdown, no further offset is applied.

It remains only to translate the node of the fixed Earth trace to the proper longitude. The amount of translation is Ω_S (See Figure B-2):

$$\Omega_S = L_S - L_S'$$

where L_S is the true longitude of the landing site, and L_S' is its longitude from the node X.

Then the coordinates of the reentry ground track are:

$$\lambda_j = \sin^{-1}\left[\sin L_T \sin \phi_j\right]$$

$$L_j = L_j' + \alpha_j + \Omega_S$$

Because of the multiplicity of calculations required to obtain tracks for the variety of conditions studied, the equations of this appendix were programmed for computer solution.

EFFECT OF VARIATION OF INPUT PARAMETERS ON REENTRY GROUND TRACKS

Figure A-6 shows a reentry track appended to the pre-reentry track for the same conditions at departure from the Moon and the same landing site. The pre-reentry and reentry tracks are continuous at the reentry point because the pre-reentry track was constrained to contain the reentry point. The curvature is discontinuous, however, because of the different ground rules used to develop the offsets in the two phases, but this fact has no effect on the conclusion of this report.

Under the assumptions used to develop the reentry track for a given landing site, only two parameters are available for variation: lunar day of departure and trajectory inclination. These have been varied over their respective permissible ranges in the course of the coverage analysis of Section 4 in the main body of the report; hence, the effect of such variation can be seen in the tracks used in that section and will not be repeated here. Instead, note will simply be made of certain restrictions that exist on these parameters.

First, the trajectory inclination cannot be less than either the latitude of the landing site or the declination of the Moon at departure, whichever is greater. Secondly, for a given approach heading, the reentry ranges associated with certain days of departure fall outside the assumed limits of 1200 to 5000 nm, and hence are inadmissible; however, because two approach headings to the landing site are generally possible, the computation must be made for the given conditions for both directions of approach to the landing site.

Appendix C

TERMINOLOGY

The following abbreviations and literal symbology are used in various sections of this report:

C&T — Meaning Communication and Tracking, this term is used only in a functional sense and does not apply to any specific station or system.

CM — Command Module

CON, LOS, — Initial CONtact with the spacecraft from a land or ship station as the spacecraft appears above the minimum masking angle at the station; LOSs Of Signal by a land or ship station as the spacecraft flies beyond the minimum antenna masking angle at the station. The term, Loss of Visibility, is used interchangeably with Loss of Signal in this report.

DSIF — Deep Space Instrumentation Facility. This applies specifically to the network of three deep-space stations at Goldstone, California; Woomera, Australia; and Johannesburg, South Africa. These stations are primarily intended to provide C&T coverage for long-range, unmanned space missions, but their capability for augmenting the coverage of the Manned Space Flight Network (MSFN) during the pre-reentry phase has been examined to some extent in this report.

IMCC — Integrated Mission Control Center, the central command and control organization for Apollo missions, located at Houston, Texas.

MSFN — Manned Space Flight Network. This abbreviation is understood to be generally accepted as applying to the total ground station network planned for manned space flight missions, including land stations for deep-space coverage and both land and ship stations for shorter-range coverage.

NL, SL — Northern Lunstice and Southern Lunstice, respectively. These are the positions of the Moon at the northernmost and southernmost declinations in its orbit around the Earth. The positions at other times are quantized in one-day increments in this report and are given designations relative to the lunstice positions. For example, SL + 1 refers to the Moon's position one day after Southern Lunstice, and SL - 1 refers to its position one day earlier than Southern Lunstice.

Node — Refers to the position of the Moon in its orbit around the Earth at the time that it crosses the Earth's equator. This occurs approximately 6-3/4 days from the lunstices.

SM — Service Module

Additional abbreviations used in specific sections of the report to facilitate discussion are defined as they appear.

Certain other terms, while not employing abbreviations, nevertheless bear definition. The principal items in this category are as follows:

Deep-space Station — Generally implying a C&T station capable of providing service at least out to lunar distances.

Extended-Range Station — Generally implying a C&T station having a range capability intermediated to that of deep-space and near-earth stations. For purposes of this report, any station requiring a range capability beyond a few thousand miles but less than 50,000 miles (the limit of the pre-reentry phase as defined below) is categorized as an extended-range station.

Near-Earth Station — Generally implying a C&T station capable of providing service only during the insertion, Earth orbit, or reentry phases — i.e., over relatively short ranges. In general, existing stations of this type are capable of providing coverage out to a few thousand miles, hence might provide some pre-reentry coverage.

Reentry point — That point in the spacecraft's return trajectory at which it reaches 400,000-foot altitude above the Earth. Its physical significance involves a somewhat arbitrary assumption that the sensible atmosphere extends to that altitude, and hence that some perturbation of the trajectory due to atmospheric drag could begin approximately at that point.

Pre-reentry, or Pre-reentry Phase — The time interval, or that portion of the return trajectory, extending from approximately 50,000 nautical miles altitude to the reentry point. This interval is expected to include the last mid-course correction maneuver.

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